✳ *Fire from Ice*

Searching for the Truth Behind the Cold Fusion Furor

by Eugene F. Mallove

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tritium or neutron results to replace their earlier measurements retracted in the spring of 1989, they said these would be published elsewhere. They remarked, however, "It is hardly tenable that the substantial number of confirmations of the calorimetric data using a variety of techniques can be explained by a collection of different systematic errors nor that tritium generation can be accounted for by any but nuclear processes."

Despite increasingly detailed accounts of cold fusion experiments like the latter paper, critics keep chanting a tattered phrase, "Show me results!" Typical was Gary Taubes's response to letters to *Science* from David Worledge of EPRI and John Bockris and Duwayne M. Anderson of Texas A&M, which were critical of his June 1990 tritium "exposé." (*Science*, August 1990.) Taubes wrote, "What is needed is the reporting of data and experiments that can speak for themselves, and a year and a half after the 'discovery' of cold fusion those data and experiments are still talked about but not seen." A more ostrichlike statement would be hard to construct.

15 *Whither Cold Fusion?*

To predict the future we need logic; but we also need faith and imagination which can sometimes defy logic itself.

Arthur C. Clarke
Profiles of the Future, 1963

. . . It can be taken for granted that before 1980, ships, aircraft, locomotives, and even automobiles will be atomically fueled.

David Sarnoff, past head of RCA, 1955

Even if [cold fusion] were only fifty-percent probable, every laboratory in the world should be working on it.

Ernest Yeager to John Bockris, 1990

✳ Here Today, Here Tomorrow

EVIDENCE THAT THE COLD FUSION STORY will be here a long time grows rather than diminishes. Recently compiled reports of positive evidence for cold fusion have come from 90 or more research groups in at least 10 nations and at five federal laboratories in the United States (pages 246–248). New dimensions of the puzzle keep popping up like dandelions on a manicured lawn. Like the sturdy product in a television ad, cold fusion is "here today, here tomorrow." Of this even most scientists are unaware. As John Bockris told a meeting of chemists in April 1990, "The general opinion of scientists around the country is that [cold fusion] is all a joke, and that it's terribly funny that people should do any work on it, because it was a gigantic mistake, which was made by two fine fellows in Utah. It's all finished now and we can look back at those times and laugh."

The *Japanese Journal of Applied Physics* featured an unusual article (April 1990) by E. Yamaguchi and T. Nishioka at the NTT Basic Re-

Groups Reporting Cold Fusion Evidence

Investigators	Institution	Heat	Tritium	Neutrons	γ-rays	^{4}He	Report Type*
Adams/Criddle	U Ottawa, Canada	X	X				4
Alquasmi	U Kiel, W. Germany		X	X			4
Alikin	Perm State U, USSR		X				3
Appleby	Ctr. El. Chem. Energy, Texas A&M	X					2
Arata	Kinki U, Japan			X			1
	Belorussian State U, USSR	X					3
Bertin	U. Bologna, Italy			X			11
Blanco	Oak Ridge NL			X			
Bockris	Texas A&M U	X	X				1,2
Bose	BARC, India		X	X			1
Cai	Chinese Acad Sci, China	X		X			2
Celani	Frascati Res Ctr			X	X		1
Claytor	Los Alamos NL		X	X			3
Cherepin	Metal Phys Inst, Kiev, Russia		X			X	3
Dash	Portland State U	X					4
De Maria	U Rome, Italy	X		X			4
Din, D.Z.	Nuclear Energy Inst, Shichuan & Beijing			X			2
Eng. Group	NCFI/U of Utah	X	X				6
Faler & Vegors	Idaho State U			X			5,6
Fukada	Kyushu U, Japan			X			4
Gao, G.T.	Eng Phys Inst, China			X			
Gou, Q.Q.	Science & Tech Inst, Chendu	X				X	2
Gozzi	U Rome, Italy	X	X	X			1
Huggins	Stanford U	X					2
Hutchinson	Oak Ridge NL	X					2
Ikegami	NFSI, Japan		XI	X			5,6
Ikezawa	Chubu U, Japan			XI			3
	Barc, India		X	X			1
Jones	Brigham Young U			X			1
Jordon	Case Western U			X			
Jorne	U Rochester			X			4
Krishan	Indira Gandhi Ctr, India			X			1

(continued)

Groups Reporting Cold Fusion Evidence, *Continued*

Investigators	Institution	Heat	Tritium	Neutrons	γ-rays	^{4}He	Report Type*
Krishnan	BARC, India		X	X			1
Kuzmin	Moscow State U	X	X	X			3
(no name)	Karpov Inst, Russia	X					3
Landau	Case Western U			X			4
Liebert	U Hawaii	X					4
Maeda	KURRI, Japan			XI			4
Mathews	Indira Gandhi Ctr, India		X	X			
McBreen	Brookhaven NL	X	X				4
McKubre	SRI International	X	X				2
Menlove	Los Alamos NL			X			2
Miles	Naval Weapons Ctr	X				(?He)	1,2
Millikan	UC Santa Barbara	X		X			4
Mizuno	Hokkaido U, Japan			X			1
	U Mexico, Mexico		X				
Nayar	BARC, India		X	X			
Nilmura	Tohoku U			X			4
Noninski	Sofia, Bulgaria						1
Ohta	U Tokyo, Japan	X					4
Okamoto	TIT, Japan			X			4
Oriani	U Minnesota	X					4
Ozawa	Hitachi, Japan			X			4
Oyama	TAT U, Japan	XI					4
Pons & Fleischmann	NCFI/U of Utah	X	X				1
(no names)	Qinhua U, Beijing, China		X	X	X		2
Radhakrishnan	BARC, India		X	X			1
Raghavan	AT&T			X			
Raj	BARC, India					X	1
Rout	BARC, India			X			1
Saini & Raye	BARC, India	X	X				6,7
Sakamoto	Tokai U, Japan			X			4
Sanchez	U Madrid, Spain		X	X			1
Santhanam	Tata Inst, India	X					
Scaramuzzi	Frascati, Italy		X	X			1
Schoessow	U Florida	X	X				6
Scott	Oak Ridge NL	X		X	X		2
Seminoz-henko	All-Union Inst, Monocrystals, Russia		X			X	3
Shyam	BARC, India			X			
Srinivasan	BARC, India		X	X			1

(continued)

search Laboratories, which has a reputation roughly like that of the AT&T Bell Laboratories in the United States. Yamaguchi and Nishioka detected a gigantic burst of over a million neutrons per second (sustained for two to three seconds) from a thin plate of palladium coated with special oxide and gold films on either side. Employing a pressurized gas cell, they had initially infused the three-centimeter square plate with deuterium. Apparently what prompted the unusual outpouring of neutrons was lowering the gas pressure around the millimeter-thin palladium. Soon two more huge neutron bursts appeared, each a few minutes after beginning depressurization. On further trials with the same plate, the investigators were unable to reproduce the effect, but the scientists conclusively associated the huge neutron emission with the explosive release of deuterium gas from one surface of the plate.

Coincident with the first neutron blast, the flat plate buckled like a potato chip and the gold coating on one surface changed color—consistent with the gold film alloying with the underlying palladium at a

Groups Reporting Cold Fusion Evidence, *Continued*

Investigators	Institution	Heat	Tritium	Neutrons	γ-rays	^{4}He	Report Type*
Storms & Talcott	Los Alamos NL	X	X				3
Szpak	Naval Systems, San Diego	X	X		X		6
Tachikawa	JAERI, Japan			XI			4
Takagi	TIT, Japan			X			4
Takahashi	Osaka U, Japan		XI	X			1
Taniguchi	OPRRT, Japan			X			1
Tian, Z.W.	Xiamen U, China			X			2
Venkateswaran	BARC, India		X	X			
Wada	Nagoya U, Japan			X			1
Wadsworth & Guruswamy	NCFI/U of Utah	X					2
Wakabayashi	PRC, Japan		XI				4
Wan	National Ching-Hwa U, Taiwan	X	X				5
Wang, D.L.	Nuclear Energy Inst, Shichuan, China			X			2
Wang, G.G.	Nanjing U, Nanjing, China	X		X			2
Werth	Englehard Industries	X					
Wolf	Texas A&M U			X			2
Xiong, R.H.	SW Nuclear Phys Inst, Shichuan, China			X			2
Yeager & Adzic	Case Western U	X	X				2
Zelenskiy	Kharkov Inst, Russia		X	X	X		3
Zhou, H.Y.	Beijing Normal U, China		X	X			2

TOTAL NUMBER OF GROUPS: 92
NUMBER OF COUNTRIES: 10 (U.S., Japan, India, Italy, USSR, Canada, W. Germany, China, Bulgaria, Spain)

Dr. F.G. Will, Director of The National Cold Fusion Institute
Courtesy of The National Cold Fusion Institute
September 12, 1990

* Key: 1 — Refereed Journal Publication
2 — Conference Proceedings
3 — Nonrefereed Report
4 — Conference Presentation
5 — Newspaper Article
6 — Personal Communication
7 — Submitted to Journal

temperature probably exceeding 1064°C. The temperature of the plate's steel sample holder rose 50°C. The heat may have had nothing directly to do with the fusion reactions that evidently gave rise to the neutrons, but it was a most unusual new phenomenon in a field that seems to grow more and more curious. "Cold Nuclear Fusion Induced by Controlled Out-Diffusion of Deuterium in Palladium" was what Yamaguchi and Nishioka called their approach.

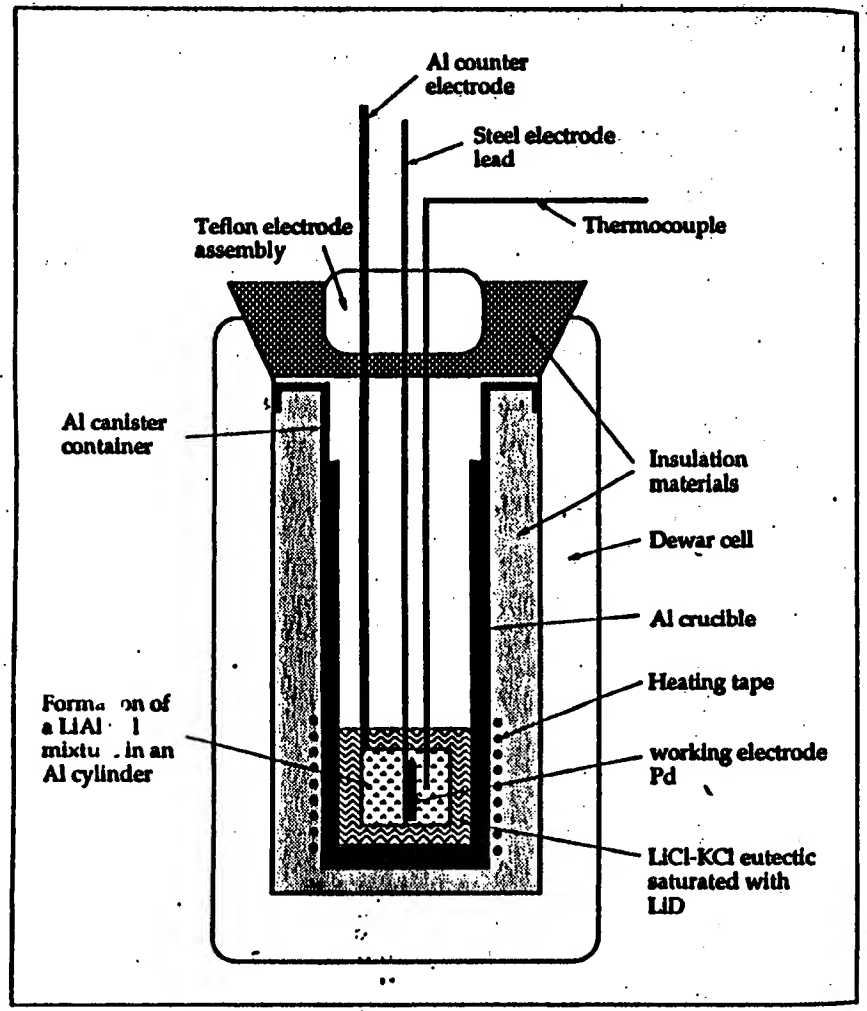
In July came *really hot* cold fusion! The cold fusioneers met in Honolulu, Hawaii, at a special session of the World Hydrogen Energy Conference that was sponsored by the Hawaii Natural Energy Institute. Associate Professor Bruce Liebert, B.Y. Liaw, and their colleagues at the University of Hawaii announced finding substantial excess heat with a high-temperature cold fusion cell that contained a molten solution of materials. They were working at temperatures from 350 to 500°C and claiming excess power bursts of up to 15 times the input power that lasted for many hours.

Again the common denominator was deuterium. Without deuterium somewhere in a system, virtually no one was reporting any kind of anomalous effects. Both palladium and titanium cathodes were tried and found to yield substantial excess power in the molten system. In one case, electrical power of 1.68 watts coursing through the cell yielded 25.4 watts of excess thermal output. The Liebert-Liaw group used a molten lithium chloride-potassium chloride mixture (LCl-KCl) that was saturated with lithium deuteride (LiD)—the latter being equivalent to the electricity-conducting material in low-temperature heavy water cold fusion cells.

Though the title of their paper was understated, "Elevated Temperature Excess Heat Production Using Molten-Salt Electrochemical Techniques," a sentence in its abstract was not: "If this effect can be reproduced at will, and duplicated at other facilities, not only would these results provide virtually irrefutable evidence for the excess heat effects attributed to *cold fusion*, they would also mean that practical use of such electrochemically-assisted processes for power generation is much closer to reality than previously anticipated." Liebert told Nick Tate of the *Boston Herald*, "We're not claiming that this is necessarily fusion. But it's some nuclear process that is occurring at the solid state, and the significance is that it's a non-chemical (reaction). Our results tend to support the cold fusion proponents a lot more than other experiments have." (July 23, 1990.)

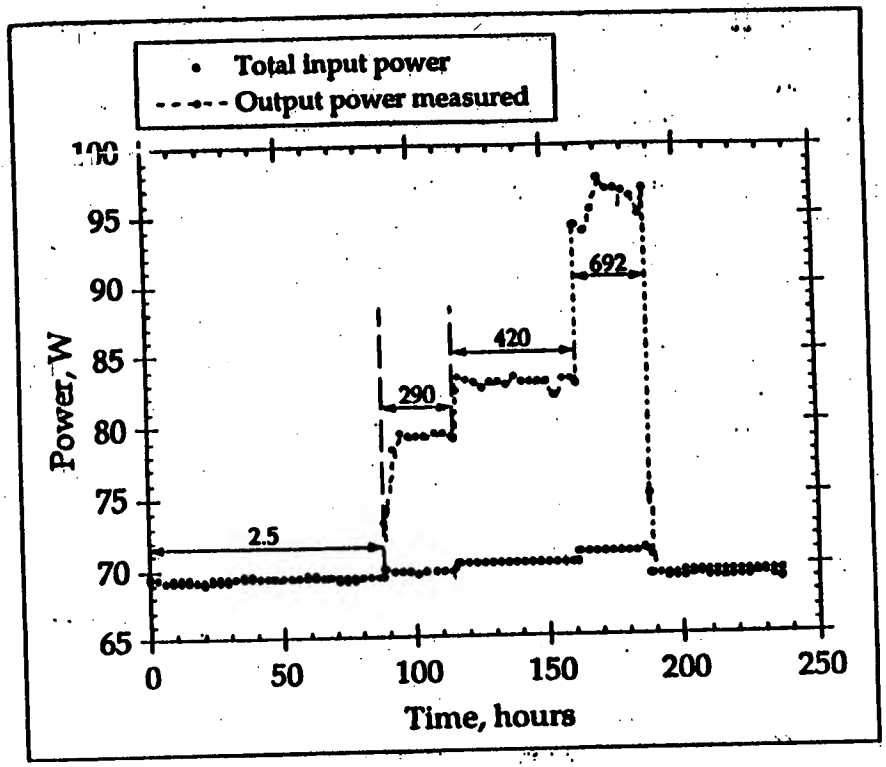
The group stated in its final paper, which appeared in the conference proceedings, "When all reactions that are known to occur in these systems are considered, no rationale can be obtained that would justify attributing a thermochemical reaction to the excess power generation. Thus, these results suggest that this effect is nonchemical . . . the origin of the excess heat generation can only be attributed to a nuclear process or, maybe, several processes, which are unknown as yet." The group's preliminary work in the same device with LiH, rather than LiD, has so far given no indication of excess heat—the kind of all-important control experiment for which critics had clamored. Shown this kind of evidence now, the critics remain dutifully silent, hoping that this annoying evidence for cold fusion will simply disappear. It won't.

If real, these molten system results are very serious power levels. They are hardly trifling, subtle effects at the limits of detection. The



The elevated-temperature molten salt electrochemical cell of B.Y. Liaw et al.—a schematic diagram. The chamber is of aluminum metal (Al) and rests in an insulated Dewar vessel. (Courtesy B.Y. Liaw, The University of Hawaii)

excess power generation in one case is reported to be over 600 watts per cubic centimeter of palladium—much more than any known heavy water cell has so far evidenced. The total energy observed coming from the system for tens of hours was about 120 megajoules per cubic centimeter (MJ/cc) or 34 kilowatt-hours per cubic centimeter Pd. Such remarkable results verge on proof that something very new and powerful is at hand. But that is not all. . . .



Comparison of the input and output power measured during high-current excursions in the molten salt electrochemical cell of B.Y. Liaw et al. Numbers in the figure are the current densities in milliamps per square centimeter at which deuterium was charged into the palladium electrode. (Courtesy B.Y. Liaw, The University of Hawaii)

✳ Proof Positive?

An irony of the cold fusion saga: The March 1990 First Annual Conference on Cold Fusion in the Salt Lake City bailiwick of Fleischmann and Pons was a turning point in cold fusion history. But at the meeting in October 1990 in neighboring Provo—BYU-Jones territory—researchers discussed results that some might call final *proof* that cold fusion is real. Evidence that tritium is being generated in cold fusion experiments became so compelling as to be essentially impossible to deny any longer. The fiction of widespread inadvertent contamination, despite every precaution and all evidence against it, and the even more tortuously conceived story of willful adulteration at a single university sank beneath the waters.

The international review meeting, "Anomalous Nuclear Effects in Deuterium/Solid Systems," chaired by Steve Jones and Nate Hoffmann

met to discuss nuclear effects issues in cold fusion studies. About 150 researchers from Argentina, China, Europe, India, Japan, Korea, the United States, and the Soviet Union gathered at Brigham Young University to hear more than 60 papers dealing exclusively with the exotic anomalous nuclear effects seen in cold fusion, not the thermal effects. Quite a threshold has been reached when scientists convene a meeting on a *subdiscipline* of cold fusion phenomena. The conference was sponsored by EPRI, DOE, and BYU. And—wonder-of-wonders—the conference proceedings were to be published by the American Institute of Physics!

A highlight of the meeting: physicist Ed Cecil of the Colorado School of Mines discussed evidence that energetic tritons—the nuclei of tritium—come out at about 5 MeV from a thin deuterium-loaded titanium foil through which an electric current is passed and which is cycled though extremes in temperature (from liquid nitrogen temperature, −196°C, to room temperature). Cecil had discussed earlier phases of his work at the Santa Fe conference in May 1989. For the present work he used a so-called silicon surface barrier detector, known to be highly resistant to neutron or gamma-ray background interference. Tritons appeared to come from localized regions in the titanium foil at consistently repeatable emission rates of many hundreds per minute. This is thousands of times above natural background. The results imply that energy is being liberated in fusion reactions at tiny sites within the metal. This represents an apparent power level of about a kilowatt per cubic centimeter in those localized regions! Cecil tried his experiment with ordinary hydrogen instead of deuterium and found—with a confidence greater than 98 percent—that high-energy "events" were associated only with the deuterium-treated titanium. In all, he registered 24 bursts of particles, with 12 of his 26 foils evidencing the phenomenon.

The Princeton University-trained physicist told a reporter, "That's the amazing thing about this; conventional wisdom says it shouldn't be fusing at all. But something is happening in there. . . . There is an awful lot of good evidence that a nuclear reaction is taking place. . . . We're at the 80 to 90 percent confidence level."

Even at the Utah conference in March 1990, George Chambers of the Naval Research Laboratory had reported charged particles with MeV energy coming out of titanium foils that he had bombarded with beams of deuterium ions. The deuterium ions going in were only in the kilovolt (350 eV) energy range. Without a fusion mechanism, you simply cannot get a 5.9 MeV particle out when the input particle is 350 eV! Chambers' conclusion then was that the charged particles coming out "could not be explained by conventional physics." That assessment has even more weight now that others have verified his results. Little doubt that the charged particles are tritons, little doubt that cold fusion is, indeed, real. His further work reported at the BYU conference corroborates Cecil's work. Kevin Wolf, however, who only recently began trying to replicate such experiments, had no positive results to report.

Howard Menlove from LANL said that he was still seeing the neutron bursts that he had discussed at the Cold Fusion Workshop in May 1989 at Santa Fe. M. Srinivasan of the Bhabha Atomic Research Center noted BARC's similar results and commented that the neutron bursts might be coming from just a few of the individual titanium chips, as his group had found. Menlove agreed. Srinivasan displayed a slide made from an "autoradiograph" of a deuterium-gas-activated chip in which apparently a significant quantity of tritium—a millicurie—had formed.

Steve Jones reported extensions of his earlier reported neutron work, such as putting his experiments in a deep mine and doing further checks for various kind of interference. Jones expressed confidence that he was continuing to see neutrons, both from deuterium gas cells and electrochemical cells. Kevin Wolf from Texas A&M reported more positive neutron results, as did F. Scaramuzzi, Dr. Zhu from the Institute for Atomic Energy in Beijing, and Dr. A. Takahashi from Osaka University and the Matsushita Electric Industrial Company in Japan.

Tom Claytor from LANL reported increasingly refined experiments in his deuterium gas cells that employ high voltages to generate tritium. His group, he said, is now able to generate tritium reproducibly. They did not get it whenever ordinary hydrogen was used.

✳ Open Questions

The compelling evidence for nuclear effects in deuterated metal systems gives enormous credibility to a possible nuclear explanation for excess heat measured in similar experiments—despite persistent attempts by Steven Jones and others to dissociate the two effects. After all, if the heat comes in such profusion that it seems to require a nuclear explanation, and if at the same time there are indisputable nuclear effects detected, even if these do not specifically explain the excess heat *quantitatively*, this seems strong presumptive evidence that the basis for the excess power may be nuclear.

Still the question remains: What is causing the excess heat if not ordinary chemistry or some bizarre, unknown form of mechanical energy storage and release? If the process be nuclear, what is the "fuel" and what are the reaction products—the "ash" of the hidden nuclear "fire." An answer could come in a two-step process: (1) First, experiments to identify the fuel and end product(s) irrespective of the complex mechanism by which the presumed fusion is brought about and (2) elucidating the physical mechanism for the reactions, for example, the specific type of lattice-deuteron behavior that promotes the reaction.

Concerning the heat, if we do not even know what we are burning, we are really nowhere in developing practical applications. If we knew the reaction and we also understood its mechanism, then we could begin to stabilize and control the process and perhaps scale it up. Maybe its intensity could be run up orders of magnitude with different materials or different geometries—alternate parameters of some kind, such as temperature. The Hawaii molten salt work provides an inkling of this.

Hagelstein, for one, now believes that the 40-plus version of his coherent fusion theory offers a mechanism and class of nuclear reactions that qualitatively, and in many aspects quantitatively, accounts for the host of possible cold fusion phenomena: rates of heat production, neutron emissions, low-energy tritium, various high-energy charged particles, and erratic behavior linked to metallurgical properties of the electrodes. Dispensing with many earlier difficulties, neutrons can be removed directly from nuclei such as deuterium and can be "donated" directly to other nuclei such as palladium. The formulation takes energy from the lattice in such a way as to make this stripping and donation of neutrons feasible. With confidence unusual even for Hagelstein, he says of the new mechanism and reaction, "I'm *certain* that this is the right one, that this is what is going on." Yet others were waiting to publish *their* supposedly solid theories, too.

Other theoreticians claim to be nearing their version of "the answer." Julian Schwinger published in late 1990 in the Proceedings of the National Academy of Sciences further theoretical insights. And Robert T. Bush with his Transmission Resonance Model for cold fusion claims to have made a major breakthrough in correlating experimental conditions and observed results.

What experiments are needed to get answers to questions posed by theories? Foremost is the need to find consistently reproducible experiments yielding heat (or nuclear products, for that matter). Sorry to say, work in this direction may continue to require a trial and error, empirical approach. It won't be easy and it's hard to say how long it will take. As Julian Schwinger observed, "The short, bloody history of cold fusion indicates that 'similarly prepared' is not a trivial condition."* Yet there are very good indications that the reproducibility problem is being put to rest. Reliable reports filtering out of the McKubre group at SRI in late 1990 were that they can now switch on and switch off the excess power pretty much *at will* by carefully controlling and monitoring electrochemical conditions.

If protons are being burned from the trace amount of light water in an experiment, how to detect their loss when the quantities disappearing are so incredibly tiny? Looking for proton loss had been a requirement of both Schwinger's and Hagelstein's theories. After this, how can we account for other possible, perhaps "auxiliary," reaction end products such as tritium, ^{3}He, and neutrons? These need to be nailed down quantitatively.

Hagelstein has suggested looking for changes in cell performance with different trace concentrations of ordinary hydrogen in the heavy water. Schwinger has suggested the same, but also proposes looking at changes in the thermal balance of presumably "dead" light water cells following small additions of heavy water. Both experimental and theoretical indications are that power levels will rise when experiments are performed at higher temperature. There is no shortage of ideas for experiments, but there is definitely a dearth of funds to carry them out. With more money, the science might have been further along already, because much time and effort has been wasted scrounging and bootlegging.

✳ Funding

A good way to begin to improve the funding situation would be to reverse the disastrous conclusions of the November 1989 ERAB report that dismissed cold fusion. The position of the panel then was untenable; it is now even more so. Reversal of the ERAB report and opening federal research funds for focused experiments is essential. This would merely be following through with what even the cold fusion critics proposed at the April 1989 Congressional hearing on cold fusion. Whether $10, $20, or $50 million is needed, who knows? Among several hundred U.S. researchers, $20 million would probably go far right now. There should be small individual grants to "basement tinkerers" too, of whom there are many already. For example, Tom Droege, a superb engineer who has built state-of-the-art instrumentation for the particle physicists at Fermilab, now works in his basement in Batavia, Illinois, as he perfects an extraordinary calorimeter. With great regularity as they monitor cold fusion cells, Tom and his brother John see excess power generation and many other interesting phenomena that neither they nor anyone else seem to be able to explain with known chemical processes. Tom claims to have spent 70 hours a week on his cold fusion experiments since the Utah announcement.

A fair amount of cooperation and close coordination between laboratories working on cold fusion already exists. Establishing mechanisms to enhance that kind of interchange and bring in all kinds of contributors to this supremely interdisciplinary field would be important, as would sharing of nuclear and chemical analysis facilities held in common.

*Julian Schwinger, "Cold Fusion: A Hypothesis," *Zeitschrift für Naturforschung*, Vol. 5, No. 5, May 1990: 756.

Journal of Fusion Energy, Vol. 9, No. 4, 1990

Coherent Fusion Theory

Peter L. Hagelstein[1]

We propose that energy from nuclear fusion reactions can be coupled to a macroscopic system coherently (in the laser sense) through electromagnetic interaction of low energy photons. We report progress on the formulation of a theory for two-step reactions in which virtual fusion is followed by exothermic incoherent decay. A new type of reaction in which incoherent electron capture is followed by coherent fusion is described.

1. INTRODUCTION

The claim of Pons and Fleischmann of the observation of fusion in an electrolysis cell[1] has been met with extreme skepticism by the scientific community.[2] The experiment has been exceptionally difficult to reproduce,[3–7] and no credible theoretical explanation of any low temperature fusion mechanism which can account for the claimed observations has been given to date.

Based on the reports of fusion at room temperature, we have been seeking new mechanisms in which fusion is enhanced in the presence of a lattice. We have proposed a coherent fusion model for p + d $\rightarrow$ ^{3}He fusion, with the nuclear energy being radiated into the lattice phonon field, one phonon at a time through electromagnetic interaction with the lattice.[8]

In this work, we report progress on the formulation of a model with which we may analyze the reaction dynamics of a class of coherent fusion reactions.

The basic premise of the theory is that off-resonant coupling between two fusing nucleons and a macroscopic system can occur through the electromagnetic interaction. An example of such a virtual fusion reaction is

$$^{a}\mathrm{H} + {}^{b}\mathrm{H} \leftrightarrow {}^{a+b}\mathrm{He}^{*} \qquad (1)$$

For example, a proton and a deuteron can fuse conventionally to ^{3}He following the emission of a 5.5 MeV gamma. If instead a low energy photon is exchanged, $^3He^*$ is still created, but only in a virtual sense. Our discussion applies to reactions involving other isotopes as well, but due to the low reduced mass and low Z of the hydrogen isotopes, we anticipate that non-hydrogenic reactions involving charged nucleons will be weaker.

In the absence of any further reaction pathways, the virtual fusion products are essentially non-observable and hence of little interest. But exothermic incoherent reaction pathways exist for most of the virtual fusion products. The two-step reactions which proceed through virtual intermediate states and are of interest here include

$$\mathrm{p} + \mathrm{p} \leftrightarrow (^2\mathrm{He})\mathrm{v} \rightarrow \mathrm{d} + \mathrm{e}^+ + \nu_e \qquad (2)$$

$$\mathrm{p} + \mathrm{d} \leftrightarrow (^3\mathrm{He})\mathrm{v} \rightarrow \mathrm{t} + \mathrm{e}^+ + \nu_e \qquad (3)$$

$$\mathrm{d} + \mathrm{d} \leftrightarrow (^4\mathrm{He})\mathrm{v} \rightarrow {}^3\mathrm{He} + \mathrm{n} \quad \rightarrow \mathrm{t} + \mathrm{p} \qquad (4)$$

$$\mathrm{d} + \mathrm{t} \leftrightarrow (^5\mathrm{He})\mathrm{v} \rightarrow {}^4\mathrm{He} + \mathrm{n} \qquad (5)$$

$$\mathrm{t} + \mathrm{t} \leftrightarrow (^6\mathrm{He})\mathrm{v} \rightarrow {}^4\mathrm{He} + 2\mathrm{n} \qquad (6)$$

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In these reactions, the notation (^{n}He)v denotes a virtual intermediate state. In the case of ^{3}He and ^{4}He ground state spatial orbitals, the time dependence will correspond to a state with an energy equal to the initial state energy minus the energy of the exchanged photon. These virtual fusion reactions are exothermic; additionally, d + d $\leftrightarrow^4$ He* would be an exothermic virtual reaction. The other intermediate states in this scenario are localized continuum states with maximum overlap with the decay products. These virtual reactions are endothermic. A schematic of the proton-deuteron reaction is shown in Fig. 1.

The incoherent branches can be either fast decays if mediated by the strong force or electromagnetic force, or else slow decays if mediated by the weak force. In the case of fast decay channels, only a small fractional virtual population needs to be established to obtain an observable decay rate. For the beta decay paths, a very large virtual population is required to produce an observable effect. The formulation which we are developing applies to both classes of reactions.

The overall scenario which we have considered works as follows: a mixture of protons and deuterons are introduced into a lattice, react virtually, and decay. The proton-proton path in this scenario produces heat, and the proton-deuterium path produces tritium. Since the beta decay is slow, a substantial virtual helium population is required to obtain observable levels of heat or tritium. The build-up of the virtual helium population would take time to occur. We estimate the (^{2}He)v decay into deuterium to take about 200 sec (from ft-theory, of Ref. 9 and 10) and therefore we require virtual (^{2}He)v levels to be in the vicinity of 10^{16} for a several-watt system for this scenario.

In this work, we have begun an analysis of this approach. A rather immediate result of the analysis is that while the coherent fusion effects are undoubtedly real, they are clearly very small under normal conditions. The tunneling into the nuclear states is so weak that even collective interactions have difficulty producing a net observable effect.

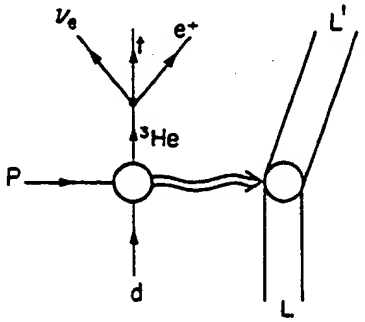

Fig. 1. Schematic of two-step fusion/beta reaction $p + d \leftrightarrow (^3He)v \rightarrow t + e^+ + \nu_e$. *L* stands for lattice in this diagram, and the electromagnetic exchange of many low energy photons is indicated here by a double photon line.

The original scenario seemed to be qualitatively consistent with the experimental report of Pons and Fleischmann when we began our study. We have recently learned that the measured gamma spectrum is inconsistent with positron production at levels which accompany such a picture (K. Wolf, Texas A&M, private communication). As a result, we have begun to consider the extension of the coherent model to other types of reactions. For example, the beta decay involving positron emission could be replaced with electron capture by the virtual fusion product. For example,

$$p + d + e \leftrightarrow (^3He + e)v \rightarrow t + \nu_e \qquad (7)$$

Alternatively, the electron capture could occur first (leading to a virtual intermediate), and the fusion reaction would follow. For example,

$$p + d + e \rightarrow (n + d + \nu_e)v \leftrightarrow t + \nu_e \qquad (8)$$

This type of reaction has the advantage that there is no coulomb barrier to inhibit tunneling between the fusing nucleons. Further discussion of alternate reactions of this type is given in the last section.

Our paper is organized as follows: In Section 2, we consider nuclear populations and polarization in the presence of a semi-classical interaction hamiltonian. The model is found to be very close to semi-classical models used in laser physics. In Section 3, we diagonalize the semi-classical hamiltonian, using a transformation which will help in analyzing more complicated systems. We next consider a quantum phonon model coupled to a classical source, and find a criterion for net phonon gain. In Section 5, we consider a coupled lattice nuclear system (Section 6), and find that the system is approximately diagonalized with our rotation of Section 3. We next investigate a driven system, and find that in the dressed state picture, external perturbations can create fusions through a second order interaction. In Section 7, we extend our analysis to include nonlinearities and strong driving terms.

2. SEMI-CLASSICAL FIELD MODEL

We first consider a system of pairs of hydrogen isotopes interacting with a semi-classical potential. The hamiltonian for the system is taken to be

$$\hat{H} = \hat{H}_N + \hat{H}_I \tag{9}$$

We will adopt a second quantization formulation (see Appendix A) for the nuclear transitions, and take $\hat{H}_N$ to be

$$\hat{H}_N = \frac{1}{2}\hbar\omega_n \sum_{kl} b_{kl}^{\dagger} b_{kl} - b_{kl} b_{kl}^{\dagger} \tag{10}$$

where the creation and annihilation operators $b\dagger$ and b are fermionic, and satisfy anticommutation relations

$$b_{kl}^{\dagger} b_{kl} + b_{kl} b_{kl}^{\dagger} = 1 \tag{11}$$

The summation is over nucleon pairs with indices k and l. The interaction matrix element can be written in the form

$$\hat{H}_I = \frac{\partial H_I}{\partial b} \sum_{kl} b_{kl}^{\dagger} + b_{kl} \tag{12}$$

In the case of M1 interaction, $\hat{H}_I = -\hat{\mu}\cdot\mathbf{B}$ where the magnetic dipole operator $\hat{\mu}$ is

$$\hat{\mu} = \mu \sum_{kl} b_{kl}^{\dagger} + b_{kl} \tag{13}$$

where the single-pair magnetic dipole moment is

$$\mu = \frac{e\hbar}{2Mc} < \phi_u | \sum_i g_i^l l_i + g_i^s s_i | \phi_f > \tag{14}$$

and where the subscripts u and f denote unfused and fused states.

We assume for simplicity that $\frac{\partial H_I}{\partial b}$ is independent of space in the vicinity of the fusing nucleons, although it can be time-dependent. The algebra for this hamiltonian is simplified if the hamiltonian is cast in terms of many-particle operators. We define three many-particle operators to be

$$\hat{\Sigma}_x = \sum_{kl} b_{kl}^{\dagger} + b_{kl} \tag{15}$$

$$\hat{\Sigma}_y = \frac{1}{i} \sum_{kl} b_{kl}^{\dagger} - b_{kl} \tag{16}$$

$$\hat{\Sigma}_z = \sum_{kl} b_{kl}^{\dagger} b_{kl} - b_{kl} b_{kl}^{\dagger} \tag{17}$$

These operators obey commutation relations similar to many-particle spin operators. In terms of these operators, the hamiltonian is

$$\hat{H} = \frac{1}{2}\hbar\omega_n \hat{\Sigma}_z + \frac{\partial H_I}{\partial b}\hat{\Sigma}_x \tag{18}$$

The time-evolution equations for the expectation values of these operators can be found through

$$\frac{d}{dt} < \hat{\Sigma}_i > = \frac{1}{i\hbar} < |\hat{\Sigma}_i, \hat{H}| > \tag{19}$$

The resulting evolution equations are

$$\frac{d}{dt} < \hat{\Sigma}_x > = -\omega_n < \hat{\Sigma}_y > \tag{20}$$

$$\frac{d}{dt} < \hat{\Sigma}_y > = \omega_n < \hat{\Sigma}_x > - \frac{2}{\hbar}\frac{\partial H_I}{\partial b} < \hat{\Sigma}_z > \tag{21}$$

$$\frac{d}{dt} < \hat{\Sigma}_z > = \frac{2}{\hbar}\frac{\partial H_I}{\partial b} < \hat{\Sigma}_y > \tag{22}$$

We shall define the population inversion and polarization averages to be

$$N^* = < \hat{\Sigma}_z > \tag{23}$$

$$M = < \hat{\Sigma}_y > \tag{24}$$

$$O = < \hat{\Sigma}_x > \tag{25}$$

Our definition for the population inversion N^* follows the definition from laser physics, and is given by the number of upper state "systems" minus lower state "systems." For example, the p + d $\leftrightarrow$ ^{4}(^{3}He)v reaction is exothermic. The population inversion is given by the number of pd pairs minus the number of (^{3}He)v nucleii. In the case of p + p $\leftrightarrow$ ^{4}(^{2}He)v, which is endothermic, N^* is the population of (^{2}He)v minus the number of pp pairs. The energy $\hbar\omega_n$ is the positive energy difference between the upper and lower states.

Following the development which is often used in laser physics, we add relaxation terms accounting for the destruction of inversion and polarization.

$$\frac{d}{dt}N^* + \frac{N^* - N_0^*}{T_1} = \frac{2}{\hbar}\frac{\partial H_I}{\partial b}M \tag{26}$$

$$\frac{d}{dt}M + \frac{M}{T_2} = \omega_n O - \frac{2}{\hbar}\frac{\partial H_I}{\partial b}N^* \tag{27}$$

$$\frac{d}{dt}O + \frac{O}{T_2} = -\omega_n M \tag{28}$$

A rate equation for N^* can be obtained under the assumption N^* varies slowly compared to the dynamics of M and O, and that

$$\frac{\partial H_I}{\partial b} = Re\left(\frac{\partial H_I}{\partial b}\right)_0 e^{-i\omega t} \tag{29}$$

Upon eliminating M and O, we obtain

$$\frac{d}{dt}N^* + \frac{N^* - N^*_0}{T_1} = -\gamma_I N^* \tag{30}$$

where

$$\gamma_I = 2\left|\frac{1}{\hbar}\left(\frac{\partial H_I}{\partial b}\right)_0\right|^2 \frac{\left[\omega_n^2 + \omega^2 + \frac{1}{T_2^2}\right]\frac{1}{T_2}}{\left[\omega_n^2 - \omega^2 + \frac{1}{T_2^2}\right]^2 + \frac{4\omega^2}{T_2^2}} \tag{31}$$

In the limit that the field varies on a timescale slow compared to the nuclear oscillation time $1/\omega_n$, this becomes

$$\gamma_I = \frac{2}{T_2}\left|\frac{1}{\hbar\omega_n}\left(\frac{\partial H_I}{\partial b}\right)_0\right|^2 \tag{32}$$

In the limit that $\frac{\partial H_I}{\partial b}$ oscillates on resonance with the nuclear polarization $\left(\omega^2 = \omega_n^2 + \frac{1}{T_2^2}\right)$, then

$$\gamma_I = \left|\frac{1}{\hbar}\left(\frac{\partial H_I}{\partial b}\right)_0\right|^2 T_2 \tag{33}$$

These limits are significant in terms of constructing a coherent fusion scenario. The two fusion-states constitute a two-level system with gain or loss initially, depending on whether the virtual reaction is exothermic or endothermic. The line width is determined by T_2 for the specific reaction. In the case of strong-force mediated decays, T_2 will be very small and the resonance will be quite broad, whereas for the reactions dominated by beta decay the lines will be very narrow.

The rate of formation of real decay products for a specific channel can be found through

$$\Gamma_i = \gamma_i|N^* - N^*_0| \tag{34}$$

where γ^i is the decay rate for the upper state fusion product. The time constant T_1 is related to the incoherent decay rates through

$$\frac{1}{T_1} = \sum_i \gamma_i \tag{35}$$

3. SEMI-CLASSICAL HAMILTONIAN DIAGONALIZATION

The form of the semi-classical hamiltonian

$$\hat{H} = \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \frac{\partial H_I}{\partial b}\hat{\Sigma}_x \tag{36}$$

suggests that diagonalization can be performed through a rotation to yield

$$\hat{H} = \frac{1}{2}\hbar\omega'_n\hat{\Sigma}'_z \tag{37}$$

where the frequency of the rotated system is

$$\omega'_n = \sqrt{\omega_n^2 + \left(\frac{2}{\hbar}\frac{\partial H_I}{\partial b}\right)^2} \tag{38}$$

The eigenvalues of the hamiltonian are

$$E_m = \frac{1}{2}\hbar\omega'_n m \tag{39}$$

where $m = -N_{kl},\cdots,N_{kl}$.

The rotation is accomplished through the use of a unitary transformation

$$\hat{H}' = e^{i\hat{R}}\hat{H}e^{-i\hat{R}} \tag{40}$$

where the operator $\hat{R}$ is linear in Σ_y

$$\hat{R} = \frac{1}{2}tan^{-1}\left[\frac{2}{\hbar\omega_n}\frac{\partial H_I}{\partial b}\right]\hat{\Sigma}_y \tag{41}$$

The picture which follows of the coupled lattice-nuclear system in this scenario is that the system possesses dressed states in which the fusion number is mixed with quantum numbers of the macroscopic system. To lowest order, a system which has an undressed fusion number equal to zero will evolve to the ground state of the dressed system with dressed fusion number equal also to zero. Due to the mixing, this dressed ground state will decay with a rate

$$\begin{aligned}\Gamma &= \sum_i \Gamma_i = \gamma_I|N^*| \\ &= \frac{2}{T_2}\left|\frac{1}{\hbar\omega_n}\left(\frac{\partial H_I}{\partial b}\right)_0\right|^2 N_{kl}\end{aligned} \tag{42}$$

assuming that $\frac{\partial H_I}{\partial b}$ is at low frequency. This decay rate is small (typical decay rates of the order of 10^{-50} – 10^{-100} sec^{-1} for charged nucleons). In order to obtain observable decay rates, transitions which change the fusion number are essential. In the following sections, we shall use the dressed state picture to obtain dressed terms which raise and lower the fusion number.

4. LATTICE DYNAMICS

We now consider the lattice dynamics under the assumption that the nuclear polarization is semi-classical. The hamiltonian for the lattice is

$$\hat{H} = \hat{H}_L + \hat{H}_I \tag{43}$$

We shall restrict ourselves to single-mode interaction in this section. In this case, the lattice hamiltonian is

$$\hat{H}_L = \hbar\omega_j a^\dagger a \tag{44}$$

where the creation and annihilation operators $a\dagger$ and a are bosonic, and satisfy the commutation relations

$$a^\dagger a - aa^\dagger = -1 \tag{45}$$

The interaction hamiltonian is will be taken to be linear

$$\hat{H}_I = \frac{\partial H_I}{\partial a}(a^\dagger + a) \tag{46}$$

where the derivative $\frac{\partial H_I}{\partial a}$ is discussed further below and in Appendix A.

As an example, we consider the case of an electric transition, such as a d + d coherent reaction which would interact through an E2 multipole. In this case, the interaction can be derived from a consideration of the potential operator, which in the coulomb limit is

$$\hat{\Phi}(r) = \sum_i \frac{Z_i e}{|r - \hat{r}_i|} \tag{47}$$

which is valid for distances $|r - \hat{r}_i|$ which are small compared to the wavelength of the exchanged photon. The more general version of Φ valid for larger distances is discussed in the Appendices. The position operator of particle i is $\hat{r}_i$. For a macroscopic system with collective modes we may write

$$\hat{r}_i \approx R_i + \sum_j \frac{\partial \hat{r}_i}{\partial a_j}(a_j^\dagger + a_j) \tag{48}$$

where R_i is the equilibrium position of particle i. This result is valid to first order in the collective mode amplitudes. As a result, we obtain

$$\frac{\partial \Phi}{\partial a_j} = \sum_i \left(\nabla_i \frac{Z_i e}{|r - r_i|}\right)_{R_i} \cdot \frac{\partial \hat{r}_i}{\partial a_j} \tag{49}$$

The expectation value of the linearized interaction hamiltonian is

$$\begin{aligned}\left\langle \frac{\partial \hat{H}_I}{\partial a} \right\rangle &= \frac{\partial H_I}{\partial a}\langle a^\dagger + a\rangle \\ &= \frac{\partial H_I}{\partial a}\Omega\end{aligned} \tag{50}$$

where we have defined $\Omega = \langle a\dagger + a\rangle$. In general $\frac{\partial H_I}{\partial a}$ will be a function of space, although we have assumed it to be uniform in the previous two sections. We will require a second quantity defined by

$$\Upsilon = \left\langle \frac{1}{i}(a^\dagger - a) \right\rangle \tag{51}$$

The time evolution of these expectation values is given by

$$\frac{d\Omega}{dt} + \omega_j \Upsilon = 0 \tag{52}$$

$$\frac{d\Upsilon}{dt} - \omega_j \Omega = \frac{2}{\hbar}\left(\frac{\partial H_I}{\partial a}\right) \tag{53}$$

Similar equations arise in laser physics, and correspond to the evolution of the electric field in a resonant cavity. In our case, the oscillation frequency of the interaction hamiltonian will in general not be well-matched to the cavity frequency ω_j. In the presence of damping, these equations become

$$\frac{d\Omega}{dt} + \frac{\omega_j \Omega}{2Q} + \omega_j \Upsilon = 0 \tag{54}$$

$$\frac{d\Upsilon}{dt} + \frac{\omega_j \Upsilon}{2Q} - \omega_j \Omega = \frac{2}{\hbar}\left(\frac{\partial H_I}{\partial a}\right) \tag{55}$$

where Q is the quality factor of the mode.

A possible coherent fusion scenario which might be proposed is one in which the nuclear polarization is driven at low frequency (ω_j). The nuclear system is initially inverted in the case of exothermic reactions and, if so, there is the possibility that the low frequency mode is driven. We can analyze this scenario within the framework of our model by noting that the classical nuclear polarization is defined in terms of the nuclear polarization expectation value

$$\begin{aligned}\frac{\partial H_I}{\partial a} &= \left\langle \frac{\partial \hat{H}_I}{\partial a} \right\rangle \\ &= \frac{\partial^2 H_I}{\partial a \partial b}\langle \Sigma_x \rangle\end{aligned} \tag{56}$$

If we assume that the interaction hamiltonian is approximately sinusoidal, then we may use the results of Section 2 to relate the lattice polarization to the nuclear polarization. If we assume that $\frac{\partial H_I}{\partial a}(t) = R_e\left(\frac{\partial H_I}{\partial a}\right)_0 e^{-i\omega t}$ with $\left(\frac{\partial H}{\partial a}\right)_0$ slowly varying in time, then we obtain

$$< \Sigma_x > = \frac{2}{\hbar}\frac{\partial^2 H_I}{\partial a \partial b}\frac{\omega_n}{\omega_n^2 - (\omega + i/T_2)^2} N^* \Omega \quad (57)$$

The criterion which must be met in order for the mode to exponentiate in the linear regime is

$$\frac{4\omega N^*}{\omega_n T_2}\left[\frac{1}{\hbar\omega_n}\frac{\partial^2 H_I}{\partial a \partial b}\right]^2 > \frac{\omega_i}{2Q} \quad (58)$$

in the case of an exothermic virtual fusion reaction. This constraint appears to be quite severe, and it is not obvious that it can be met without substantial enhancements in tunneling.

5. COUPLED-LATTICE–NUCLEAR DYNAMICS

The hamiltonian for the combined nuclear and lattice system is

$$\hat{H} = \hat{H}_N + \hat{H}_L + \hat{H}_I \quad (59)$$

In terms of the operators defined in the previous sections, this can be written as

$$\hat{H} = \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \frac{\partial^2 H_I}{\partial a \partial b}\hat{\Sigma}_x(a^\dagger + a) + \hbar\omega\rho^\dagger a \quad (60)$$

We may diagonalize the first two terms of the hamiltonian using a rotation similar to the transformation of Section 3. This leads to a transformed hamiltonian given by

$$\begin{aligned}\hat{H}' &= e^{i\hat{R}}\hat{H}e^{-i\hat{R}} \\ &= \frac{1}{2}\hbar\omega_n'\hat{\Sigma}_z + \hbar\omega\rho^{i\hat{R}}a^\dagger a e^{-i\hat{R}}\end{aligned} \quad (61)$$

The rotation operator in this case is

$$\hat{R} = \frac{1}{2}\tan^{-1}\left[\frac{2}{\hbar}\frac{\partial^2 H_I}{\partial a \partial b}(a^\dagger + a)\right]\hat{\Sigma}_y \quad (62)$$

We note that ω'_n is an operator in this formulation

$$\omega_n' = \sqrt{\omega_n^2 + \left(\frac{2}{\hbar}\right)^2\left(\frac{\partial \hat{H}_I}{\partial b}\right)^2} \quad (63)$$

We can compute the leading terms of Eq. (61) by assuming that $\hat{R}$ is small, specifically using

$$e^{i\hat{R}}a^\dagger a e^{-i\hat{R}} = a^\dagger a + i[\hat{R}, a^\dagger a] + \ldots \quad (64)$$

The resulting transformed hamiltonian is

$$\hat{H}' = \frac{1}{2}\hbar\omega_n'\hat{\Sigma}_z + \hbar\omega\rho^\dagger a + \frac{\omega_I}{\omega_n}\frac{\partial^2 H_I}{\partial a \partial b}\hat{\Sigma}_y\frac{(a^\dagger - a)}{i} \quad (65)$$

valid to first order in Σ_y. The interaction term which arises is smaller than the original interaction by a factor of ω_i/ω_n. One could perform a second rotation and eliminate this coupling term, but given the smallness of the interaction, it does not appear at this point to be necessary.

To lowest order, little happens in a system initially in the unfused state ($\Sigma_z\Psi_0 = \pm N_{kl}\Psi_0$) of the transformed system. In the dressed state picture, the coupled system remains in the initial state (which has a small component which decays according to the results of Section 2), and essentially no further fusion occurs. Larger total decay rates would be obtained if transitions to states of higher fusion number could be made; such transitions require additional terms in the hamiltonian, which we consider in the following sections.

6. A DRIVEN COUPLED NUCLEAR–LATTICE SYSTEM

In the presence of an external driving term, the hamiltonian is

$$\hat{H} = \hat{H}_N + \hat{H}_L + \hat{H}_I + \hat{H}_{ext} \quad (66)$$

As before we will recast $\hat{H}$ in terms of the operators defined previously. This yields

$$\begin{aligned}\hat{H} = &\frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \frac{\partial^2 H_I}{\partial a \partial b}\hat{\Sigma}_x(a^\dagger + a) + \hbar\omega\rho^\dagger a \\ &+ \left(\frac{\partial H_{ext}}{\partial a}\right)^{(1)}(a^\dagger + a) + \left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\frac{(a^\dagger - a)}{i}\end{aligned} \quad (67)$$

where we have kept only first order terms in the external hamiltonian. The first term of the external hamiltonian is proportional to $(a\dagger + a)$, which is a position operator.

The second term is proportional to $(a\dagger - a)/i$ which is a velocity operator.

Using the rotation of Section 5 leads to a transformed hamiltonian

$$\begin{aligned}\hat{H}' &= e^{i\hat{R}}\hat{H}e^{-i\hat{R}} \\ &= \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \hbar\omega\beta^\dagger a \\ &+ \frac{\omega_l}{\omega_n}\frac{\partial^2 H_I}{\partial a\partial b}\hat{\Sigma}_y\frac{(a^\dagger - a)}{i} \\ &+ \left(\frac{\partial H_{ext}}{\partial a}\right)^{(1)}(a^\dagger + a) \\ &+ e^{i\hat{R}}\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\frac{(a^\dagger - a)}{i}e^{-i\hat{R}}\end{aligned} \tag{68}$$

In this result, we have kept only the lowest order term arising from the transformation of $\hat{H}_L$. Additionally, $(a\dagger + a)$ commutes with $\hat{R}$, so that the first external term is unchanged after the transformation. To lowest order, we find

$$\begin{aligned}&e^{i\hat{R}}\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\frac{(a^\dagger - a)}{i}e^{-i\hat{R}} \\ &\quad = \left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\frac{(a^\dagger - a)}{i} + \left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}[\hat{R}, a^\dagger - a]\end{aligned} \tag{69}$$

After performing the commutation we obtain the low order transformed hamiltonian

$$\begin{aligned}\hat{H}' &= \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \hbar\omega\beta^\dagger a + \frac{\omega_l}{\omega_n}\frac{\partial^2 H_I}{\partial a\partial b}\hat{\Sigma}_y\frac{(a^\dagger - a)}{i} \\ &+ \left(\frac{\partial H_{ext}}{\partial a}\right)^{(1)}(a^\dagger + a) + \left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\frac{(a^\dagger - a)}{i} \\ &- \frac{2}{\hbar\omega_n}\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\frac{\partial^2 H_I}{\partial a\partial b}\hat{\Sigma}_y\end{aligned} \tag{70}$$

The new addition to our dressed-state hamiltonian is a term which combines the out-of-phase (velocity-dependent) external driving hamiltonian to a fusion polarization operator.

Some comments on this new term are in order. It is basically a second order effect relative to the initial lattice-nuclear coupling, except that it has the potential of being amplified since $\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}$ may be very large. The increase in observable decay rate due to the external hamiltonian is

$$\Gamma' = \frac{8N_{kl}}{T_2}\left[\frac{1}{\hbar\omega_n}\frac{\partial^2 H_I}{\partial a\partial b}\right]^2\frac{1}{(\hbar\omega_n)^2}\left[\left(\frac{\partial H_{ext}}{\partial a}\right)^{(2)}\right]^2 \tag{71}$$

This effect increases the decay rate, but since it is assumed to be off-resonant, it appears difficult to produce substantial observable effects without enhancements of the tunneling probability.

7. NONLINEARITIES AND STRONG DRIVING TERMS

The only way that large enough decay rates to produce observable effects can follow from a coherent fusion theory in the absence of strong tunneling enhancement, especially in the case of weak interaction decay reactions, is if high frequency potential oscillations are developed. Such effects are not produced by first order terms in the hamiltonian, and hence one would not expect to see any coherent fusion effects in an unstressed macroscopic system in the elastic limit. Hence we are forced to consider the possibility of adding terms which are of extreme order in a and $a\dagger$.

Having postulated that the presence of high order nonlinearities is required to make further progress in the theory, we face the difficulty of analyzing the system which is proposed. We shall begin the analysis, and we have a formulation which may in the future lead to a more tractable theory, but the discussion of this section must be viewed as the beginning of a larger and possibly involved effort.

The hamiltonian which we postulate is written as

$$\begin{aligned}\hat{H} = \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \frac{\partial^2 H_I}{\partial a\partial b}\hat{\Sigma}_x(a^\dagger + a) \\ + \hat{H}_L + \hat{H}_{ext}\end{aligned} \tag{72}$$

where $\hat{H}_L$ and $\hat{H}_{ext}$ are now assumed to be highly nonlinear in a and $a\dagger$. The dressed state hamiltonian is to lowest order

$$\hat{H}' = \frac{1}{2}\hbar\omega_n + \hat{H}_L + i[\hat{R}, \hat{H}_L] + i[\hat{R}, \hat{H}_{ext}] \tag{73}$$

where $\hat{R}$ is given in Eq. (62). Let us define

$$\hat{\Xi} = i\left[\frac{1}{2}\tan^{-1}\left[\frac{2}{\hbar\omega_n}\frac{\partial^2 H_I}{\partial a\partial b}(a^\dagger + a)\right], \hat{H}_L + \hat{H}_{ext}\right] \tag{74}$$

The dressed state hamiltonian becomes

$$\hat{H}' = \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \hat{H}_L + \hat{\Xi}\hat{\Sigma}_y \qquad (75)$$

From this form of the dressed state hamiltonian we may obtain the resonance virtual fusion decay rate to be

$$\Gamma' = \frac{N_{kl}T_2}{\hbar^2}\,|<\hat{\Xi}(\omega = \sqrt{\omega_n^2 + 1/T_2^2}>|^2 \qquad (76)$$

For a frequency-dependent nonlinear interaction matrix element, we may generalize this result to

$$\Gamma' = \frac{2N_{kl}}{\hbar^2}\int_0^\infty |<\Xi(\omega)>|^2 \frac{[\omega_n^2 + \omega^2 + 1/T_2^2]}{[\omega_n^2 - \omega^2 + 1/T_2^2]^2 + 4\omega^2/T_2^2}d\omega \qquad (77)$$

This result is useful as a formal result for the incoherent decay of a coupled system. It is not easily amenable to further quantification in the absence of models for $\hat{H}_L$ and $\hat{H}_{ext}$ which are tractable.

We note that there is an alternate approach to the computation of the dressed state interaction term. In this case, we discard a and $a\dagger$ as the primary macroscopic operators, and work instead directly with the individual particle position and momentum operators. We consider the coupled lattice-nuclear hamiltonian

$$\hat{H} = \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \frac{\partial\hat{H}_I}{\partial b}\hat{\Sigma}_x + \sum_i \frac{|\hat{p}_i|^2}{2m_i} + \sum_{i<j}V(|\hat{r}_i - \hat{r}_j|) + \hat{H}_{ext} \qquad (78)$$

In this formulation, the coordinate positions r_i and momenta p_i are taken to be the primary operators.

The infinitesmal rotation operator is

$$\hat{R} = \frac{1}{2}\tan^{-1}\left[\frac{2}{\hbar\omega_n}\frac{\partial\hat{H}_I}{\partial b}\right]\hat{\Sigma}_y \qquad (79)$$

The transformed hamiltonian becomes to lowest order in $\hat{\Sigma}_y$

$$\hat{H}' = \frac{1}{2}\hbar\omega_n\hat{\Sigma}_z + \sum_i \frac{|\hat{p}_i|^2}{2m_i} + \sum_{i<j}V(|\hat{r}_i - \hat{r}_j|) + \hat{H}_{ext} + i\frac{\hat{\Sigma}_y}{\hbar\omega_n}\left[\frac{\partial\hat{H}_I}{\partial b}, \sum_i \frac{|\hat{p}_i|^2}{2m_i}\right] + i\frac{\hat{\Sigma}_y}{\hbar\omega_n}\left[\frac{\partial\hat{H}_I}{\partial b}, \hat{H}_{ext}\right] \qquad (80)$$

for the case of electric E1, E2, . . . transitions involving very low energy photon exchange (since $\frac{\partial\hat{H}_I}{\partial b}$ is only a function of coordinates $\hat{r}_i$, and not momenta $\hat{p}_i$). The extension to the magnetic case is straightforward.

In terms of the coordinate-based operators, the dressed state interaction operator $\hat{\Xi}$ is

$$\hat{\Xi} = i\frac{1}{\hbar\omega_n}\left[\frac{\partial\hat{H}_I}{\partial b}, \sum_i \frac{|\hat{p}_i|^2}{2m_i}\right] + i\frac{1}{\hbar\omega_n}\left[\frac{\partial\hat{H}_I}{\partial b}, \hat{H}_{ext}\right] \qquad (81)$$

In this formulation, a single dressed state fusion transition is coupled to a macroscopic transition operator. If the exchange involves a large amount of energy ($\hbar\omega_n$), then it is possible for the interaction to be resonant with the nuclear system. In the dressed state formulation, even though such a transition involves a great deal of energy, the net interaction is made of a large number of low energy coulombic photon exchanges with the nucleii. As a result, the effective interaction can be long range.

8. SUMMARY AND CONCLUSIONS

We have described progress which we have made toward the development of a coherent fusion theory. The premise of this type of theory is that a fusion reaction which can occur through the emission of a high energy gamma can also proceed, at least in principle, through the successive emission of a large number of low energy photons. In of itself, such an observation is not immediately useful, since the multi-photon process will be of high order and hence occur only weakly. If a large number of identical fusion reactions are involved in the process, then a significant enhancement of the low energy photon emission rate may be possible if the low energy photons are emitted coherently.

There are, however, two distinct problems which must be faced in order to account for the Pons–Fleischmann effect within the framework of the coherent fusion picture. Not only must nuclear energy be coupled from the microscopic to the macroscopic coherently, but some way must be found in order to overcome the coulomb barrier. Our efforts included consideration of proton-proton fusion, since it appeared to have the largest tunneling probability of all fusion reactions between charged nucleons. Although it was obvious at the outset of the work that it would be very difficult to obtain an effect sufficiently large to be observable from such premises, we found motivation from the similarities between the reported experimental observations and the qualitative features of a coherent fusion theory. We had hoped that through our investigations that some new piece of phys-

ics would turn up which would account for an enhancement in tunneling.

In fact, after this paper had been written and submitted, it occurred to us that two-step beta/fusion reactions involving an intermediate neutron might provide an answer to the tunneling problem. There was not time to develop a model for the new reaction and to write a new paper; it was decided to retain most of the initial paper and to supplement it with some discussion of the new ideas. Our hope is that these ideas can help in the development of a quantitative theory for the Pons–Fleischmann effect.

We have modeled systems in which coherent fusion is followed by incoherent decay. Our principal result in this area is simply making a connection between laser physics and the fusion problem. Additionally, we have found that the rates for coherent two-step fusion/beta reactions are very small, under a variety of assumptions. One of our goals was to attempt to exploit collective effects without altering the tunneling probabilities substantially in accounting for the Pons–Fleischmann effect. In this respect, we have not succeeded in the case of fusion/beta reactions.

These conclusions prompted us to consider the coherent fusion mechanism on an alternate class of virtual reactions, for example, a related two-step proton-deuteron reaction which we propose

$$e + p + d \rightarrow (n + d + \nu_e)v \leftrightarrow t + \nu_e \quad (82)$$

In this type of reaction, the electron capture would precede the virtual fusion reaction. It is illustrated in Fig. 2. The advantage of this type of reaction is that the fusion would occur between a neutral particle and a charged particle, and hence there is the possibility of obtaining a substantial tunneling probability for the coherent fusion branch of the reaction. This reaction would be responsible for tritium production in our new scenario.

Heat production would follow from a similar beta/fusion reaction, specifically

$$e + p + p \rightarrow (n + p + \nu_e)v \leftrightarrow d + \nu_e \quad (83)$$

as shown in Fig. 3.

This reaction might proceed as follows: a proton would tunnel into the outer electron orbitals of a nearby metal atom, and pick up an electron through the weak interaction electron capture process. The resulting state would be virtual, since it is not energetically allowed. The fusion of the neutron and a second proton would occur through the coherent fusion (electromagnetic M1 interaction) mechanism discussed in this paper, driven by a relatively large magnetic dipole associated with neutral system tunneling. Overall, this process is somewhat related to two-photon decay. The neutrino spectrum would be continuous, and the remaining nuclear energy would be converted to heat through interaction with the current.

The basic mechanism can in principle be extended to higher Z systems. For example, a two-step reaction involving lithium is proposed:

$$e + p + {}^6\mathrm{Li} \rightarrow (n + {}^6\mathrm{Li} + \nu_e)v \leftrightarrow {}^7\mathrm{Li} + \nu_e \quad (84)$$

This reaction is of interest since it can be mediated by electromagnetic E1 interaction for s-wave neutron-lithium channels, which we believe should be dominant.

The principle can be extended to higher Z coherent fusion reactions. For example, the two-step reaction

$$e + p + {}^{104}\mathrm{Pd} \rightarrow (n + {}^{104}\mathrm{Pd} + \nu_e)v \leftrightarrow {}^{105}\mathrm{Pd} + \nu_e \quad (85)$$

could occur through electromagnetic E2 interaction for s-wave channels. (This proposal is in part motivated by the recent experimental observations of O'Grady at Naval Research Laboratory.) The other stable Pd isotopes could react similarly.

We have focused on proton reactions in our ex-

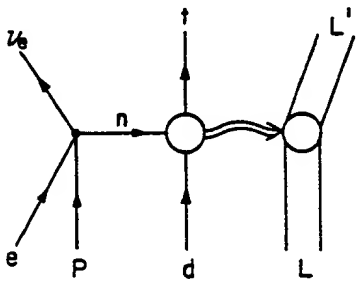

Fig. 2. Two step coherent beta/fusion reaction $p+d+e \rightarrow (n + d + \nu_e)v \leftrightarrow t + \nu_e$.

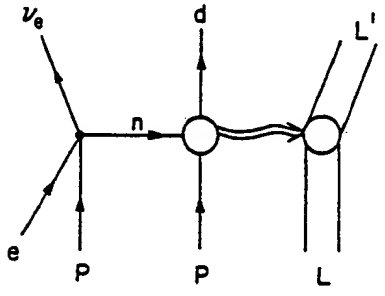

Fig. 3. Two-step coherent beta/fusion reaction $p+p+e \rightarrow (n + p + \nu_e)v \leftrightarrow d + \nu_e$.

amples because proton would appear to be favored due to the small reduced mass. Similar reactions initiated by electron capture of deuterium or tritium are also possible, as illustrated in Fig. 4.

We provide some initial discussion of the formulation of a model for this type of reaction in Appendix B. Some work remains in the development of coherent fusion theory before it becomes quantitative (the reader may provide his/her own judgment on how much). Our focus has been on mechanism, and experiments can shed light on the correctness of our premises (Is deuterium produced consistent with heat? Are neutrinos produced at substantial rates?).

In conclusion, we have proposed and explored a new scenario and several new reactions in an attempt to account for the Pons–Fleischmann effect.

APPENDIX A. SECOND QUANTIZATION OPERATORS

The quantities which appear in Section 2 can be determined from the matrix element derived from the lowest order Feynman diagram for single photon exchange. This matrix element is

$$\langle \Gamma \mid H_I \mid \Gamma' \rangle = \tag{A.1}$$
$$\sum_i \sum_{kl} \langle \Gamma \mid \left[\frac{2}{\pi} \frac{f(K \mid \mathbf{r}_i - \mathbf{r}_k \mid)}{\mid \mathbf{r}_i - \mathbf{r}_k \mid} \right] \left[\rho_i \rho_k - \frac{\mathbf{j}_i \cdot \mathbf{j}_k}{c^2} \right] \mid \Gamma' \rangle$$
$$+ \sum_i \sum_{kl} \langle \Gamma \mid \left[\frac{2}{\pi} \frac{f(K \mid \mathbf{r}_i - \mathbf{r}_l \mid)}{\mid \mathbf{r}_i - \mathbf{r}_l \mid} \right] \left[\rho_i \rho_l - \frac{\mathbf{j}_l \cdot \mathbf{j}_l}{c^2} \right] \mid \Gamma' \rangle$$

In this formula, the summation over i includes all particles in the lattice, the summation over k and l is over all pairs of hydrogen isotopes, and K is the wavevector

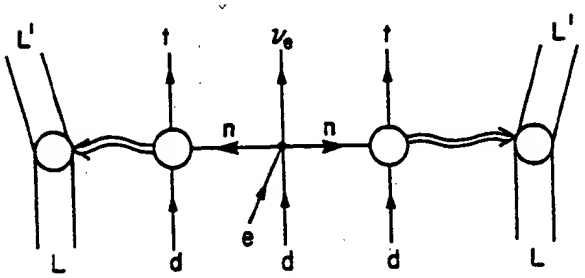

Fig. 4. Example of a coherent fusion reaction involving electron capture by a deuteron.

$(2\pi/\lambda)$ of the exchanged photon. The function f is defined in terms of cosine and sine integrals.

$$f(z) = Ci(z)\sin(z) - si(z)\cos(z) \tag{A.2}$$

In the low energy limit ($K \to 0$) we note that

$$\lim_{K \to 0} \frac{2}{\pi} \frac{f(K \mid \mathbf{r}_i - \mathbf{r}_k \mid)}{\mid \mathbf{r}_i - \mathbf{r}_k \mid} = \frac{1}{\mid \mathbf{r}_i - \mathbf{r}_k \mid} \tag{A.3}$$

For relativistic electrons, $\mathbf{j}$ and ρ_i commute with $\mathbf{r}^i$, but in other cases (A.1), must be symmetrized with respect to noncommenting variables.

Our goal is to build up a model in which the fusion energy is coupled from the microscopic to the macroscopic. This will be easiest to accomplish when the interaction is long range, which immediately suggests that we should concentrate on low energy photon exchange (where λ is greater than the system dimensions). For example, coupling to mechanical or acoustical modes can be done with relatively low energy photons; plasmon generation in a metal will involve photons of several electron volts and will therefore be of shorter range.

The interactions described in (A.1) are electrical or magnetic at low energy. The longest range interaction is the monopole interaction. For example, in the low energy limit where (A.3) is appropriate, then

$$\frac{1}{\mid \mathbf{r}_i - \mathbf{r}_k \mid} = \sum_{lm} \frac{4\pi}{(2l+1)} \frac{r_<^l}{r_>^{l+1}} Y^*_{lm}(\mathbf{r}_i) Y_{lm}(\mathbf{r}_k) \tag{A.4}$$

The monopole case is where $l=0$, and the interaction strength is proportional to $1/r$. Unfortunately, the matrix element on the microscopic scale is normally zero for an E0 transition for well-separated particles. A microscopic electric dipole (E1) transition couples to free charge with a $1/r^2$ dependence, but it requires p-wave interaction between the nucleons at the microscopic scale for light hydrogen (p and d) isotope reactions. For two-step reactions where fusion occurs first, only the s-wave interactions have any chance of contributing at low temperature. As a result, the electric quadrupole (E2) interaction will in general do best of the electric interactions for these systems, and it varies as $1/r^3$.

The allowed magnetic interactions under the assumption of microscopic s-wave interaction to even parity final states are odd-multiple (M1, M3, . . .) interactions. The magnetic dipole (M1) interaction will be the strongest, and is proportional to $1/r^2$ at low energy. The dipole occurs at the nuclear microscopic half of the total interaction, while the macroscopic part of the interaction involves macroscopic current flow. Spin-spin interaction is also possible, but varies as $1/r^3$.

The dominant long-range interaction (in the absence

of electric and magnetic monopole transitions) is the M1 interaction, for even parity final states for which the interaction hamiltonian at low energy is customarily taken to be

$$H_I = -\mu \cdot B \tag{A.5}$$

In the case of the two-step reactions described in Section 8, the neutron need not necessarily be at low energy relative to the charged nucleus. At low energy, the above arguments still hold, but at high energy p-wave terms are possible, and the coupling can in principle occur through E1 interaction.

We can simplify the matrix element through the use of the Hartree approximation. In this approximation, we separate the total macroscopic wavefunction $|\Gamma\rangle$ into a product of a local part $|\phi_\Gamma\rangle_{kl}$ which includes the two fusing hydrogen isotopes, and $|\bar{\Gamma}\rangle$ which includes the remaining part of $|\Gamma\rangle$. The electrical part of the interaction in this approximation is

$$\langle \Gamma \mid H_E \mid \Gamma' \rangle = \sum_{kl} \sum_{LM} \langle \phi_\Gamma \mid \rho_{LM} \mid \phi_{\Gamma'} \rangle_{kl} \Phi_{LM}(r_{kl}) \tag{A.6}$$

where

$$\Phi_{LM}(r) = \sum_i \langle \bar{\Gamma} \mid \frac{Z_i e Y_{LM}\left(\frac{r - r_i}{|r - r_i|}\right)}{|r - r_i|^{L+1}} \mid \bar{\Gamma}' \rangle \tag{A.7}$$

and where

$$\rho_{LM} = Q^E_{LM} = \sum_i \frac{e}{2} [1 + \tau_3(i)] r_i^L Y_{LM}(\hat{r}_i) \tag{A.8}$$

in the low energy limit. In this formula, we have assumed in addition that the principal interaction is long range such that $|r_i - r_k| = |r_i - r_l| = |r_i - r_{kl}|$. The coordinate r_{kl} in this formula denotes the location of the fusion product.

In the limit that the wavelength of the exchanged photon is long compared to the nuclear scale, but otherwise arbitrary, then (A.4) is replaced by

$$\frac{2}{\pi} \frac{f(K \mid r_i - r_k \mid)}{|r_i - r_k|} = \sum_{lm} 8 \int_0^\infty \frac{k}{K + k} j_l(kr_1) j_l(kr_2) dk Y^*_{lm}(\hat{r}_1) Y_{lm}(\hat{r}_2) \tag{A.9}$$

and Φ_{LM} becomes

$$\Phi_{LM}(r) = \frac{\sqrt{\pi}}{\Gamma\left(L + \frac{3}{2}\right) 2^{L+1}} \sum_i \langle \bar{\Gamma} | Z_i e Y_{LM}\left(\frac{r - r_i}{|r - r_i|}\right) \int_0^\infty \frac{k^{L+1}}{\omega + k} j_L(k|r - r_i|) dk | \bar{\Gamma}' \rangle \tag{A.10}$$

The magnetic part of the interaction becomes

$$\langle \Gamma \mid H_M \mid \Gamma' \rangle = -\frac{1}{c} \sum_{kl} \sum_{LM} \langle \phi_\Gamma \mid J_{LM} \mid \phi_{\Gamma'} \rangle_{kl} \cdot A_{LM}(r_{kl}) \tag{A.11}$$

where

$$\langle \phi_\Gamma \mid J_{LM} \mid \phi_{\Gamma'} \rangle_{kl} = \sum_i \frac{1}{2} \langle \phi_\Gamma \mid r_i^L Y^*_{LM} j_i + j_i r_i^L Y_{LM} \mid \phi_{\Gamma'} \rangle \tag{A.12}$$

and

$$A_{LM}(r) = \sum_i \langle \bar{\Gamma} \mid j_i \frac{Y_{LM}}{|r - r_i|^{L+1}} + \frac{Y_{LM}}{|r - r_i|^{L+1}} j_i \mid \Gamma \rangle \tag{A.13}$$

The generalization to the case where the wavelength of the exchanged photon is much larger than nuclear size scales, but otherwise arbitrary, is obtain through the use of (A.9), as before.

We have defined matrix elements thus far which allow us to handle both electric and magnetic coupling for arbitrary multipolarity. We are ignoring free photon emission in the present work. At this point we shall focus on the magnetic M1 interaction, although it is clear that we are in a position to adapt our formulation to other cases.

The M1 matrix element is

$$\langle \Gamma | H_M | \Gamma' \rangle = -\frac{1}{c} \sum_{kl} \sum_{M=-1}^{1} \langle \phi_\Gamma | J_{1M} | \phi_{\Gamma'} \rangle_{kl} \cdot A_{1M}(r_{kl}) = -\sum_{kl} \langle \phi_\Gamma | \mu | \phi_{\Gamma'} \rangle_{kl} \cdot B(r_{kl}) \tag{A.14}$$

where

$$B(r) = \frac{1}{c} \nabla \times \sum_i \langle \bar{\Gamma} \mid \frac{1}{2} \left(j_i \frac{1}{|r - r_i|} + \frac{1}{|r - r_i|} j_i \right) \mid \bar{\Gamma}' \rangle \tag{A.15}$$

and the magnetic moment is

$$\mu = \sum_i g_i^{(l)} l_i + g_i^{(s)} s_i \qquad \text{(A.16)}$$

Some simplification is afforded if the dipole moments are taken to be uniform for all pairs. For example, in *HD* gas at very low temperature all pairs would be in the ground state, and all molecules with identical relative J will possess identical moments. In this limit, we may define a spatially dependent polarization operator to be.

$$0(r) = \sum_{kl} \delta^3(r - r_{kl}) \qquad \text{(A.17)}$$

In terms of these operators, the interaction matrix element becomes

$$\langle \Gamma \mid H_I \mid \Gamma' \rangle = \mu \cdot \int 0(r) \langle \overline{\Gamma} \mid B(r) \mid \overline{\Gamma}' \rangle d^3r \qquad \text{(A.18)}$$

The transition to a second quantization picture can now be made. At the location r_{kl}, the two hydrogen isotopes can either be fused or not. The interaction matrix element is of interest when a fusion transition occurs, either creation of a fused state (we shall adopt $b_{kl}^\dagger$ to describe the transition to a fused state) or destruction of a fused state (b will be the annihilation operator). The second quantized version of the polarization operator is

$$\hat{0}(r) = \sum_{kl} \delta^3(r - r_{kl})(b_{kl}^\dagger + b_{kl}) \qquad \text{(A.19)}$$

The $b_{kl}^\dagger$ operators must be fermionic, since once two hydrogen isotopes have fused, they are assumed not to be able to fuse further.

If we define spatially dependent versions of the inversion and polarization operators

$$\hat{N}^*(r) = \sum_{kl} \delta^3(r - r_{kl})(b_{kl}^\dagger b_{kl} - b_{kl} b_{kl}^\dagger) \qquad \text{(A.20)}$$

and

$$\hat{M}(r) = \sum_{kl} \delta^3(r - r_{kl}) \frac{(b_{kl}^\dagger - b_{kl})}{i} \qquad \text{(A.21)}$$

then we would obtain a spatially-dependent version of the Eqs. (26–28).

If B(r) is considered to be an operator (in terms of $\hat{r}_i$), then the interaction matrix element becomes

$$\langle \Gamma \mid H_I \mid \Gamma' \rangle = [\Gamma \mid \mu \cdot \int \hat{0}(r)\hat{B}(r) d^3r \mid \Gamma' \rangle \qquad \text{(A.22)}$$

This is ultimately the basis for discussion of Section 7.

We have chosen to work with an assumption that the interaction is uniform in the vicinity of the fusing hydrogen isotopes. This corresponds to the Dicke superradiant limit of this type of model, and allows us to exploit the rotation transformations introduced in Section 3. Under this assumption, (A.14) becomes

$$\langle \Gamma \mid H_I \mid \Gamma' \rangle = \langle \Gamma \mid \mu \cdot \int \hat{0}(r) d^3r \hat{B} \mid \Gamma' \rangle \qquad \text{(A.23)}$$

The integral in (A.13) is computed

$$\int \hat{0}(r) d^3r = \sum_{kl} (b_{kl}^\dagger + b_{kl}) \qquad \text{(A.24)}$$

which is a space-independent version of $\hat{0}$ which we have used in Section 2. Using $\hat{\mu} = \mu \sum_{kl} (b_{kl}^\dagger + b_{kl})$, we obtain

$$\langle \Gamma \mid H_I \mid \Gamma \rangle = \langle \Gamma \mid \hat{\mu}\hat{B} \mid \Gamma' \rangle \qquad \text{(A.25)}$$

which is the premise of Eq. (12).

In order to free ourselves from a particular multipolarity, we will work in terms of $\hat{H}_I$. For magnetic dipole interaction, we define

$$\begin{aligned} \hat{H}_I &= \sum_{kl} \frac{\partial \hat{H}_I}{\partial b_{kl}} (b_{kl}^\dagger + b_{kl}) \\ &\approx \frac{\partial \hat{H}_I}{\partial b} \hat{0} = \frac{\partial \hat{H}_I}{\partial b} \hat{\Sigma}_x \end{aligned} \qquad \text{(A.26)}$$

For Section 4, we have

$$\begin{aligned} \hat{H}_I &= \sum_{ij} (\nabla_i \hat{H}_I) \cdot \frac{\partial r_i}{\partial a_j} (a_j^\dagger + a_j) \\ &= \sum_j \frac{\partial \hat{H}_I}{\partial a_j} (a_j^\dagger + a_j) \end{aligned} \qquad \text{(A.27)}$$

For Section 5, we extend this to

$$\begin{aligned} \hat{H}_I &= \sum_i \sum_{kl} \frac{\partial^2 \hat{H}_I}{\partial a_i \partial b_{kl}} (a_i^\dagger + a_i)(b_{kl}^\dagger + b_{kl}) \\ &\approx \frac{\partial^2 \hat{H}_I}{\partial a \partial b} \left(\sum_i a_i^\dagger + a_i \right) \hat{\Sigma}_x \end{aligned} \qquad \text{(A.28)}$$

With this type of formulation, we may describe E1, E2, and M1 interactions on the same formal basis.

APPENDIX B.

We wish to explore the extension of our formulation to reactions where electron capture occurs before fusion. Our formulation will focus on the generic two-step reaction.

$$e + p + {}^a X \rightarrow (n + \nu_e + {}^a X)\nu \leftrightarrow \nu_e + {}^{a+1} X \qquad \text{(B.1)}$$

This reaction is fundamentally more complicated than the fusion/beta reactions considered earlier since the neutron all neutrino and neutron energies must be included.

We begin by considering the microscropic problem of three initial particles (e, p, and ^{a}X). The Schrödinger equation which we shall adopt is written as

$$i\hbar\frac{\partial}{\partial t}\begin{bmatrix}\Psi_1\\ \Psi_2\\ \Psi_3\end{bmatrix} = \tag{B.2}$$

$$\begin{bmatrix}H_1 & H_W & 0\\ H_W & H_2 & \hat{H}_I\\ 0 & \hat{H}_I & H_3\end{bmatrix}\begin{bmatrix}\Psi_1\\ \Psi_2\\ \Psi_3\end{bmatrix} + \hat{H}_L\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}\begin{bmatrix}\Psi_1\\ \Psi_2\\ \Psi_3\end{bmatrix}$$

We have expanded out the creation and annihilation operator explicitly in this notation. The hamiltonian H_1 contains terms appropriate for the three initial particles (e, p, and ^{a}X) and the lattice, and Ψ_1 contains coordinates for the initial three particles and the lattice. The hamiltonians H_2 and H_3 contain terms appropriate for the three intermediate (and final) state particles (n, υ_e,^{a}X), in the crude picture that $^{a+1}$X is simply a bound state of the n + ^{a}X system. The collection of particles described by H_2 and H_3 are identical, and in this sense H_2 and H_3 are the same unless we find some way to distinguish between the spaces on which they operate. We shall employ projection operators P and Q which will give meaning to our separating H_2 and H_3. Specifically, we define

$$H_2 = PHP \tag{B.3}$$

$$H_3 = QHQ \tag{B.4}$$

where P projects out states in which the neutron is bound.

The electron capture occurs through the weak interaction, which is accounted for in the off-diagonal H_w in (Eq.) (B.2).The electromagnetic transitions which drive the coherent fusion process are in $\hat{H}_I$. The hats in this equation refer to lattice operators. As before, the coupling between a fusion reaction and the lattice is assumed to be dominated by low order and low energy lattice transitions.

The generalization of the transformation to the dressed state picture is accomplished through a rotation similar to the one used in Section 3. The infinitesmal rotation operator of interest would be

$$\hat{R} = \frac{1}{2}\tan^{-1}\left[\frac{2}{H_2 - H_3}\hat{H}_I\right]\begin{bmatrix}0&0&0\\0&0&i\\0&-i&0\end{bmatrix} \tag{B.5}$$

if $\hat{H}_I$ commuted with $H_2 - H_3$. The transformed hamiltonian would then be approximately

$$\hat{H}' = \begin{bmatrix}H_1 & H_W & 0\\ H_W & H_2 & 0\\ 0 & 0 & H_3\end{bmatrix} + \hat{H}_L\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} + i\frac{1}{H_2 - H_3}[\hat{H}_I, \hat{H}_L]\begin{bmatrix}0&0&0\\0&0&i\\0&-i&0\end{bmatrix} \tag{B.6}$$

We would then extend our definition of the local dressed state interaction operator $\hat{\Xi}_H$ to be

$$\hat{\Xi}_H = i\frac{1}{H_2 - H_3}[\hat{H}_I, \hat{H}_L + \hat{H}_{ext}] \tag{B.7}$$

following Equation (81), and where we have included an external driving hamiltonian.

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NOTE ADDED IN PROOF

Some of the ideas presented at the May, 1989 Sante Fe conference were extended in a presentation given in San Francisco in December, 1989. The present work was written in November of 1989, and is the paper distributed by ASME (paper 89-WA/TS-4) at the conference. The ideas have been taken much further since that time, and the interested reader is referred to "Status of Coherent Fusion Theory," in the proceedings of the First Annual Cold Fusion Conference, Salt Lake City, March 1990, and to "Coherent Fusion Mechanisms," presented at the October 1990 workshop on Anamolous Effects in Deuterated Metals at BYU.

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Nuclear and Thermal Effects During Electrolytic Reduction of Deuterium at Palladium Cathode

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In a galvanostatic experiment of charging deuterium in a palladium cathode, nuclear and thermal effects were found. A sintered palladium electrode shaped as parallelepiped was used. After 6 days of electolysis at 200 mA/cm², a simultaneous emission of neutrons, tritium excess in the electrolytic solution, and temperature rapid increase was observed. During the event which lasted 4 minutes, we counted 7.2×10^5 neutrons while the electrode temperature reached 150°C. Electrochemical procedure for charging the palladium electrode by deuterium using galvanostatic pulses as well as the associated electrode temperature trends are shown.

KEY WORDS: Cold fusion; Pd-D system; Pd electrochemistry.

1 INTRODUCTION

On the frame of the F and P[1,2] experiment, we try to perform experiments of so-called "cold fusion" through the electrolytic reduction of deuterium at a palladium cathode. The experimental procedure differs from that used in Ref. 1 in the following points: (1) a sintered palladium electrode (a parallelepiped of 6X5X25mm) was used instead of a cast metal electrode, (2) temperature of the electrode was measured instead of the temperature of the electrolyte solution, and (3) calorimetric measurements were not carried out.

For the detection of nuclear phenomena, neutron and gamma emission were monitored. In addition, data acquisition system was programmed in such a way as to switch off the electrolysis for an electrode temperature up to 80°C.

The experimental electrochemical part is essentially constituted by a three-electrodes assembly to carry out galvanostatic measurements, in which the working electrode is the palladium electrode having a S-type thermocouple embedded in it. The counter electrode is a cylindical platinum mesh while the reference electrode is a mercury–mercury oxide electrode in alkaline solution. The electrolyte is an LiOD 0.1 M solution and the cell is placed in a waterbath which acts as thermostat. In Fig. 1, a scheme of the electrolysis cell is reported. As shown in the figure, the electrode, whose terminal part along the major axis has been machined, is sealed to a glass tube. The thermocouple is also sealed into the electrode. The thermocouple is protected by fused glass in such a way as to eliminate any interaction between thermocouple wires and deuterium. In a previous light-water experiment, in which no thermocouple protection was used, the thermocouple signals were disturbed by high noise.

Referring to the nuclear measurements, we detected neutron emission by a ^{3}He dosimeter with an energy range up to 7 MeV.

The efficiency was measured to be 10^{-4} in isotropic conditions by an Am-Be source. In our experimental geometry, we estimated an efficiency of 5×10^{-5}. This neutron detector is connected to a rate meter counter-recorder system. It was previously checked that each spike on the recording corresponds a count on the counter. The γ-ray measurement was also carried out through a large sodium iodide monocrystal connected to a SILENA spectrum analyzer. The apparatuses for the nuclear measurements were placed around the electrochemical cell

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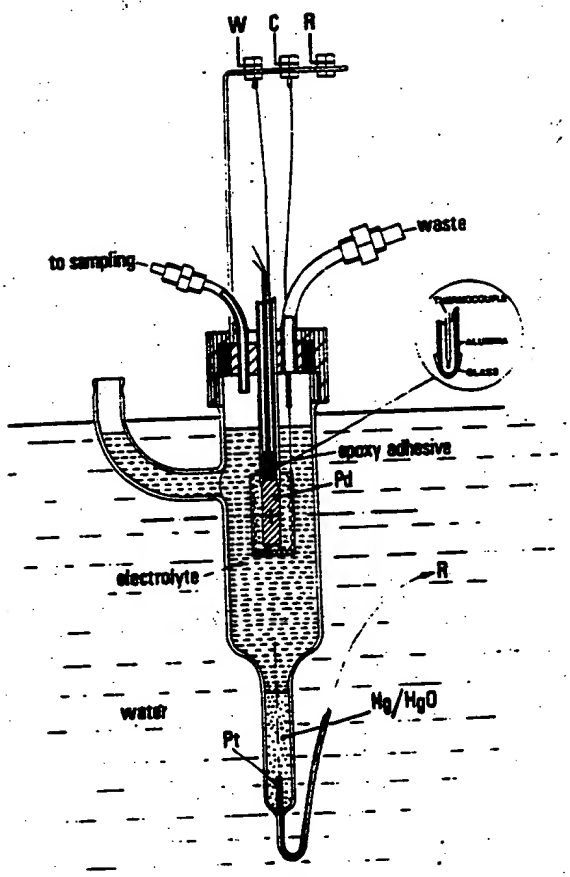

Fig. 1. Electrolytic cell assembly.

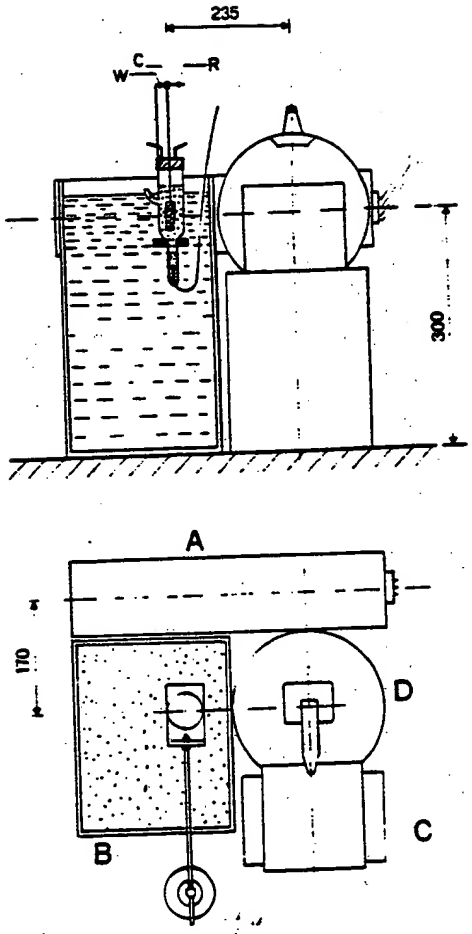

Fig. 2. Neutron and γ-ray detector positioning. (A) NaI (Tl) monocrystal, (B) Waterbath, (C) He^3 neutron dosimeter, and (D) polyethylene sphere

as schematized in Fig. 2. Through a data acquistion system, electrochemical parameter and temperature value were transferred in the computer while the neutron detector signals were recorded. Therefore, there is not a synchronized data acquisition for temperature, electrochemical parameters, and neutrons.

During the experiment, some electrochemical measurements were also carried out concerning the possibility of obtaining information about the deuterium content in the palladium electrode, i.e., the palladium "deuterium-charge" state. A well-known electrochemical method was used to charge the Pd electrode electrochemically. This is shown in Fig. 3 where the palladium electrode potential and the temperature is reported vs. time when galvanostatic pulses of different durations are applied to the cell. Two parts are distinguishable in Fig. 3 (upper, part A) in which the current was switched off (EMF measurement) and part B where the current was passing (Fig. 4). In the same Fig. 3 (bottom), the related temperature variations during those steps, are also shown. Figures 4 and 5 which are, respectively, enlarged views of sections B and C of Fig. 3 show that there is a progressive change of the shape of the chrono-potenziometric curve during the D charging in palladium. There is an initial peak which disappears progressively. The associated electrode temperature curves seem to reproduce this behavior. A tentative explanation of this could be found in the change of the D chemical potential gradient in Pd electrode as D charging proceeds. This procedure changes in the diffusion overvoltage which is a part of the total electrode overvoltage. By plotting the EMF values vs. the passed coulomb charge, the charging curve, shown in Fig. 6, was obtained. This curve could be a way to check the time evolution of the deuterium content in the Pd electrode.

After 150 hours of electolysis at 200 mA/cm^2, a nuclear and thermal effect was simultaneously recorded, as shown in Fig. 7.

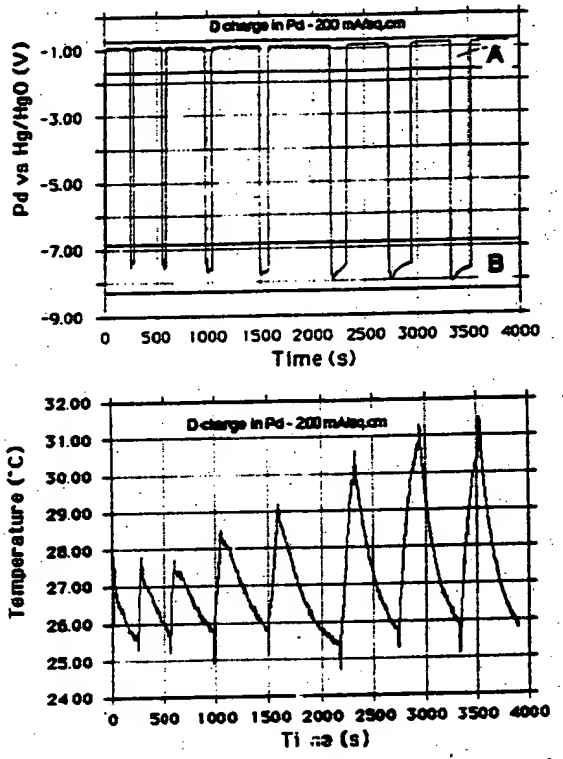

Fig. 3. Palladium potential (upper) and electrode temperature vs. time, recorded when galvanostatic steps were applied to the cell. (upper): Section A: $i=0$, section B: $i=200$ mA/cm².

At a certain time, the temperature grew very sharp, and because the recorder was set at the lowest full scale of 1 mV, the pen went full scale. At the same time, a densification of the spikes was measured by the neutron recorder; this is only a part of the total recording. Data refers to a time acquisition of 22h 5' 54", and 116 was displayed on the counter. If we count each spike in the recording, we have 80 spikes. At a time interval of an estimated of 4 min were concentrated 36 spikes. Before and after the event, the neutron counting was that of the background level of 3.0 ± 0.2 counts per hour and during the 4 minutes of the event we had 36 counts. Therefore, in that time interval, we had a neutron emission equal to about 180 times the background level. By extrapolating the heating and cooling curves it was possible to obtain the maximum temperature reached by the electrode as shown in Fig. 8. At 135 s, current was switched off by the data acquisition system since temperature was over 80°C while the neutron emission lasted approximately 105 s. If we estimate a temperature increase of about 100°C, by taking into account the mass of the palladium electrode and its specific heat, we have an energy produced of 176 J $=1.1 \times 10^{21}$ eV. In addition, by taking into account the efficiency of the detector we find that 7.2×10^5 neutrons have been emitted. Furthermore, considering the evaluated energy (176J) to be due to the nuclear fusion process $d+d \rightarrow He^3 + n$, we would have a neutron emission of 1.4×10^{15}.

At the time these proceedings were prepared, we can definitely confirm a tritium excess corresponding to $(2.14 \pm 0.04) \times 10^{11}$ atoms related to the solution volume of 41 ml. More detailed information concernig the experimental and other results have been the subject of a paper recently submitted.[3]

2. DISCUSSION

MR. TURKEVICH: Are there any questions?

MR. PETRASSO: Richard Petrasso from MIT. I'm a little confused about your neutron rate. You said first 150 times background and it took an efficiency of 10^{-4}, and I get aroun 10^3 neutrons per second, and that's...

MR. GOZZI: Per hour.

MR. PETRASSO: Right.

MR. GOZZI: 3.5 neutrons per hour.

MR. PETRASSO: Okay, thank you.

MR. TURKEVICH: Any other questions?

MR. GARWIN: Dick Garwin, IBM Research. I can imagine that the catastropic event in which the temperature rose 100 degrees or so was not fusion at all but simply a response to having stuffed deuterons into high-energy sites in the lattice, similar to vigner (phonetic) energy in graphite in reactors. And you see the neutrons, but they may have nothing at all to do with the heat that caused the temperature to rise. To discriminate between these two cases would be to find 10^{14} helium 4.

What has happened to that sample? Have you looked for helium 4 in that sample?

MR. GOZZI: I don't know exactly the process that you mentioned but one can think about several chemical processes that can increase the temperature of the electrode if the effect is concentrated in a short time. But the more realistic process that I can imagine is the direct combination of hydrogen and oxygen due to the high catalytic activity of the deuterated electrode. But this process, also by the experience of some of my colleagues, is possible only if the electrode is exposed to the gaseous atmosphere.

After the event, I switched on the current again, and the current was applied for 24 hours. But any other event was observed.

MR. GARWIN: There is a very good poster upstairs which says if you had helium 4 in there, you still

ELECTROLYTIC TRITIUM PRODUCTION

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COLD FUSION
TECHNICAL NOTE
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Fifty-three electrolytic cells of various configurations and electrode compositions were examined for tritium production. Significant tritium was found in 11 cells at levels between 1.5 and 80 times the starting concentration after enrichment corrections are made.

INTRODUCTION

The possible production of nuclear products and heat in an electrolytic cell, as first proposed by Fleischmann and Pons[1] and Jones et al.[2] is so hard to accept that extraordinary experimental efforts need to be made to prove that the phenomenon exists. This is especially important in view of several complete studies that have failed to report positive results.[3-6] This study is being reported to add to the growing number of observations[7-13] that tritium, at least, can be made in an electrolytic cell.

Tritium appears to be the least ambiguous and most easily measured product of the "cold fusion" effect. In addition, the production of tritium has implications at least as important as the production of heat, although these two products may not originate from the same process. The authors recognize that this work is still incomplete and leaves many questions unanswered. However, the results are supported by such a large and consistent data base that reporting of tritium production is warranted even before a full understanding of the process is available.

The early phase of this study was started shortly after the announcement of possible fusion in palladium. Simple construction and inexpensive diagnostic methods were dictated by funding restraints. Initially, we tried to understand how to achieve a high deuterium-to-palladium (D/Pd) ratio. A cell was designed that would allow the cathode to be weighed, thus giving a measure of the deuterium content. This consisted of a wide mouth, 120-ml glass jar with a small electrical socket in the lid that allowed the cathode assembly to be plugged in. Periodically this assembly was unplugged, washed with acetone, dried, and weighed. Unfortunately, the electrolyte was found to attack the solder and copper in the plug thereby causing copper, zinc, and lead to plate onto the cathode surface. Thus, all early cathodes had a surface contamination of these elements. This surface impurity was reduced but not eliminated in some later cells by coating the lead and plug with Torr Seal (an epoxy). Although one electrode having detected copper, zinc, and lead on the surface produced tritium, subsequent cells were redesigned to eliminate this contamination. An additional problem occurred because the Torr Seal absorbed deuterium, causing the apparent D/Pd ratio to be too large. We concluded that D/Pd ratios above 0.82 were not only unlikely to occur at room temperature, but appeared to be unnecessary to produce tritium. After the first tritium was observed, emphasis shifted to reproducing this event.

This technical note concentrates on those cells that produced tritium. Over 1500 electrolyte samples have been analyzed for tritium, which has given an excellent statistical basis for evaluating tritium production.

Three sets of experimental data are described:

1. 16 early cells that gave, in two cases, relatively large amounts of tritium and, in two cases, small amounts, but were not well characterized
2. a set of 13 closed cells with recombination[a] that gave no tritium but provided a good example of counting statistics
3. 9 cells with external recombination that were followed in detail but gave only small amounts of tritium in seven cells.

EXPERIMENTAL DETAILS

Data Set 1

The first tritium was produced in the cell design shown in Fig. 1. A 120-ml glass jar contained a 60-ml plastic insert

[a]The catalytic recombiners are graphite cloth containing Teflon on which platinum is deposited. These were purchased from Prototech Company, 70 Jaconnet St., Newton Highlands, Massachusetts 02161, as 20% platinum on carbon (0.35 mg/cm^2 on woven cloth).

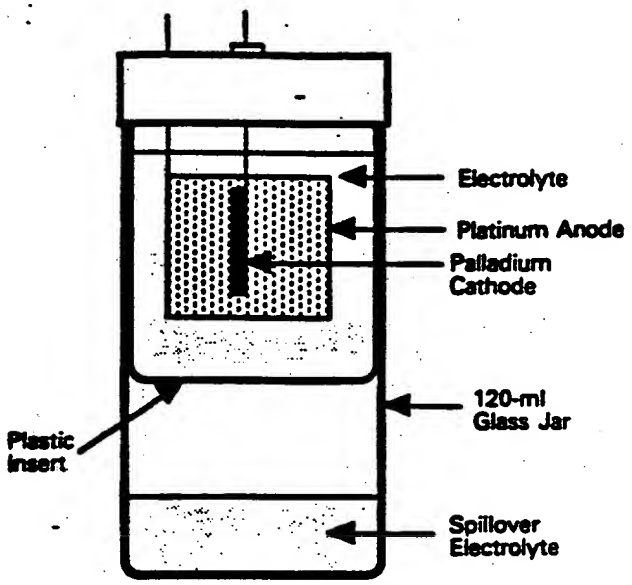

Fig. 1. Cell design 1.

into which the electrolyte[b] (0.2 *N* LiOD[c]) was placed. Gases generated in the cell were allowed to leave through a small hole. The anode was a gauze of platinum metal, ~2.5 cm long and 2.5 cm in diameter. The cathode was made by arc-melting powder[d] and rolling the resulting button into a coin-shaped disk ≈2 mm thick and 1.5 cm in diameter. This was spot welded to a platinum wire that was soldered to a small plug. The assembly was plugged into a small socket that was sealed through the lid using Torr Seal. Torr Seal was applied to the platinum lead between the cathode and the plug. In spite of this precaution, copper and lead were found on the surface of cathode 30 when the electrode was examined after tritium production had stopped. We do not know whether the continuing increase of these contaminates might have eventually stopped tritium production. However, none of the cells having bare leads, where these contaminates are present in greater quantity, showed signs of tritium production.

Cells of this design typically showed a slow transfer of electrolyte from the plastic insert to the bottom of the glass jar. This transferred liquid is called the spillover. Tritium contained in this liquid would have accumulated gradually as the slow transfer occurred. Usually ~20 to 30 ml had transferred by the time these cells were terminated.

Several of the palladium coins were pretreated by heating them in H_2S that was made by heating sulfur and paraffin together. The resulting mixture of H_2S and paraffin vapor produced a black layer that, when sufficiently thick, was an electrical insulator. Deuterium uptake would not occur unless the electrode was electrolyzed using reversed current (anodic). This caused most of the black layer to flake off and the subsequent cathodic electrolysis to charge the electrode with deuterium in the normal way. Unfortunately, this work was being done during the early, exploratory stages when minimal funding was available for detailed surface characterization. This treatment was done in an attempt to poison atomic recombination at the surface and increase the D/Pd ratio. Details of this study will be described in subsequent papers.

Tritium measurements[e] were started ~10 days after the first cells of this series were turned on. Table I shows the materials used in the cells, and Table II lists the count rate based on 10-min counts. Although many of the cells did not produce tritium, they are included to show that cells running at the same time were not contaminated by the common source of D_2O, lithium, electrode materials, or materials used for the surface treatment.

Four (29, 30, 41, and 43) cells show an indication of tritium production. The values that we believe show excess tritium production are indicated by bold type. Cell 30 gives a disintegration rate[f] of 1.1×10^4 dis/min·ml (× 80 increase), which, as indicated, is ~50 times the tritium content of unused electrolyte. This level was found when measurements were stated 10 days after the cell was turned on. No additional tritium was produced during the next 3 days. A current reversal after this time produced no additional tritium. Cell 29 showed only a little excess tritium in the electrolyte. This, we believe, was due to a small amount of original electrolyte in the new solution. A little of the original electrolyte remained in the cell after decanting it from the material that flaked off during anodic operation. This change was made ~30 h before the first tritium measurements were made. Production of significant tritium in this cell before the change is indicated by activity in the spillover that gave a disintegration rate of 6.5×10^3 dis/min·ml (× 47). This spillover had accumulated since the cell was turned on and had not been changed. Some small activity was found in cells 41 and 43, being 540 dis/min·ml (× 4) and 280 dis/min·ml (× 2), respectively. Unfortunately, cell 41 was turned off just as an indication of increased production was occurring.

The charging history of the two most active cells is shown in Fig. 2. The sudden increase in the D/Pd shown by cell 29 after 100 h and the slow rise shown by cell 30 after 150 h are, we believe, an artifact caused by the Torr Seal. The electrolyte in cell 29 was changed two additional times. Another

[b]Heavy water (>99.9% deuterium) was obtained from MSD Isotopes, Montreal, Canada. An analysis showed the following values in parts per million: Ag, Al, As, Au, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hf, Hg, Ho, Ir, La, Li, Lu, Mg, Mn, Mo, Nd, Ni, Os, Pb, Pd, Pr, Pt, Rb, Re, Rh, Ru, Sb, Sc, Se, Sm, Sn, Sr, Ta, Tb, Te, Th, Ti, Tl, Tm, U, V, W, Yb, Zn, Zr) < 1, (Si, B, Na) = 3.

[c]The lithium metal contained the following in weight percent: 99.8689% lithium (99.982 at.% ^{7}Li), 0.0100% heavy metals, <0.010% chlorine, 0.0265% carbon, and 0.0732% nitrogen. The following metals were detected: calcium = 84, iron = 20, potassium = 8, sodium = 77, silicon = 25 ppm.

[d]The powder was obtained from Johnson Matthey (stated as 100% palladium), batch V7114307. Detected elements were as follows: silver = 60, aluminum = 20, iron = 25, sodium = 65, platinum = 35, and silicon = 35 ppm (wt). Undetected elements: As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Ga, Gd, Ge, Hf, Hg, Ho, Ir, La, Li, Lu, Mg, Mn, Mo, Nb, Nd, Ni, Os, Pb, Pr, Rb, Re, Rh, Ru, Sb, Sc, Se, Sm, Sn, Tl, Tm, U, V, W, Yb, Zn, and Zr (all <10 ppm).

[e]Tritium was determined by mixing 1 ml of the sample with 10 ml of scintillator fluid in a plastic vial. The light pulses produced by the tritium beta-scintillator fluid interaction were counted using a Packard Tri-Carb Liquid Scintillation Spectrometer, model 3255. Standards obtained from the National Bureau of Standards were run with the samples and used to calibrate the machine.

[f]The decomposition rate is calculated by subtracting 20, the average background, from the sample counting rate and dividing by 0.38, the counting efficiency. Conversion to other units can be done using 100 dis/min = 4.50×10^{-5} μCi = 1.67 Bq.

TABLE I

Materials[a] Used in Cells 26 to 44

Number	Shape[a]	Weight (g)	Area (cm^2)	Alloy	Surface Treatment	Pretreatment	Electrode Poison	Lead Covering	Maximum D/Pd	Excess Tritium[b]
26	Coin	4.9	3.7	Li/Pd = 0.047	std[c]	None	Thio[d]	Torr seal	0.82	N
27	Coin	6.4		Nickel	std	None	None	Torr seal	0.09	N
28	Coin	6.4	5.0	Rh/Pd = 0.1	std	None	Thio	Torr seal		N
29	Coin	5.0	4.8	Palladium	Sulfide	$H_2S + C$[e]	Thio	Torr seal		Y
30	Coin	6.8	5.1	Palladium	Sulfide	$H_2S + C$	None	Torr seal		Y
31	Coin	6.2	5.0	Pd + Rh + Li	std	None	Thio	Torr seal		N
33	Coin	6.1	5.0	Li/Pd = 0.051	std	None	Thio, Cu, Pb[f]	No	0.77	N
34	Coin	6.2	5.0	Li/Pd = 0.023	std	None	Thio, Cu, Pb	No	0.83	N
35	Coin	6.4	5.0	Li/Pd = 0.012	std	None	Thio, Cu, Pb	No	0.77	N
36	Coin	7.0	6.0	Rh/Pd = 0.1	std	None	Thio, Cu, Pb	No	0.86	N
37	Coin	6.6	5.5	Rh/Pd = 0.1	std	None	Thio, Cu, Pb	No	0.90	N
40	Coin	8.4	7.0	Palladium	Sulfide	$H_2S + C$	None, Cu, Pb	No	0.84	N
41	Wire	3.2	7.6	Palladium	None	None	Thio	Torr seal	0.86	Y
42	Coin	6.1	5.0	S/Pd = 0.0043	std	None	None	Torr seal		N
43	Coin			B/Pd = 0.026	std	None	As_2O_3	Torr seal		Y
44	Coin	6.5	5.2	Palladium	Sulfide	$H_2S + C$	None	Torr seal	0.75	N

[a]All anodes are platinum and the cells are plastic.
[b]Coin = arc-melted powder and rolled into coin shape, and wire = 0.032-in. diameter.
[b]Cells that are thought to produce excess tritium are indicated by "Y."
[c]std = sanded with 200 grit paper and washed with HNO_3.
[d]Thio = 0.0004 g/ml thiourea added to electrolyte.
[e]$H_2S + C$ = heated in vapor produced by a mixture of paraffin and sulfur.
[f]Cu, Pb = probable impurity on cathode surface due to attack of solder and connector. The measured D/Pd is probably too high because of this deposition.

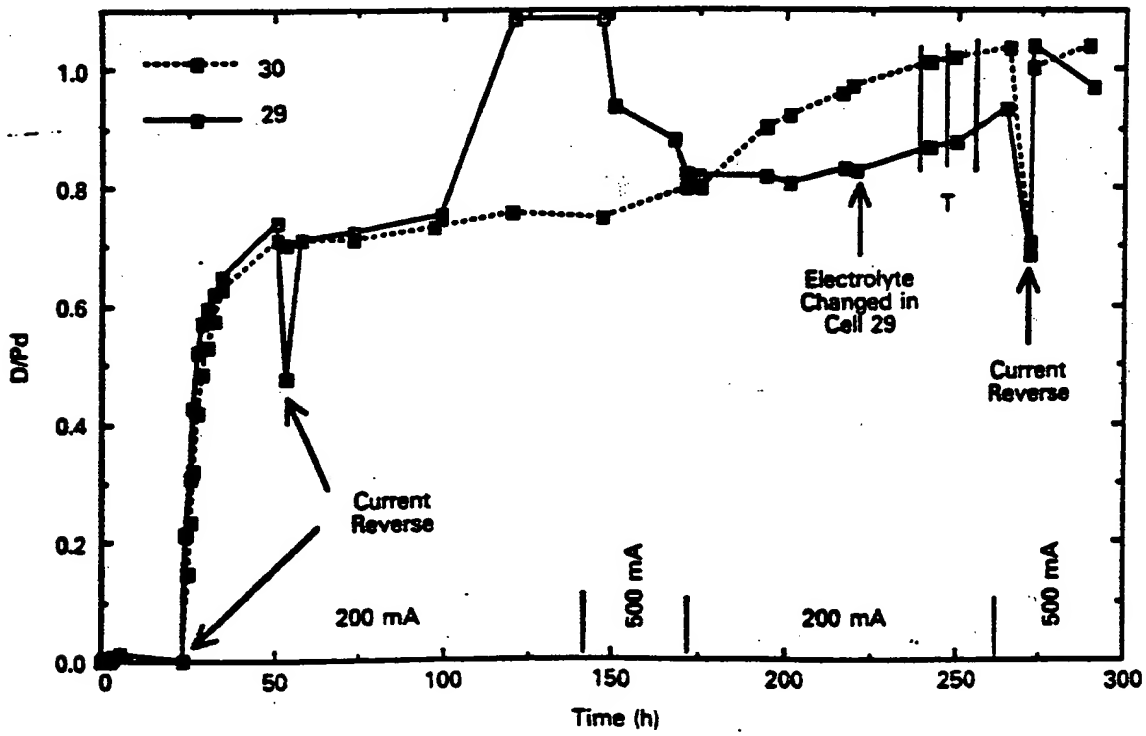

Fig. 2. Charging history of cells 29 and 30. Tritium measurements were made at times indicated by the vertical lines and the letter "T."

TABLE II

Cells Running When Tritium Measurements Were Started (gross count/min·ml)
(10-min count using 1 ml of electrolyte)

Date	Day	Cell Number															
		26	27	28	29	30	31	33	34	35	36	37	40	41	42	43	44
		Start =															
		June 1	June 1	June 2	June 5	June 5	June 8	June 15	June 15	June 15	June 17	June 17	June 20	June 21	June 24	June 24	June 26
June 13	0	77c[a]	80	78c	c												
June 14	1	77	79	71	182		97										
June 15	2	76c	77	74c	154	4204	68										
June 16	3	103	99	87	125	3711	81	68	73	71							
June 17	4	80	78c	57	122	3730	80c	75c	78c	77c							
June 18	5	92	83	88	c	130c	83	91	85	85							
June 19	6	71c	67	70	67	111	72	75	70	67c	76	69					
June 20	7	73	71	72	75	78	73	c		80	80	80					
June 21	8	73	70c	70	70	80	80	69		72	83c	76	65				
June 22	9	64	68	69c	71c		75c	66		67	67	95	111	70			
June 23	10			120	74	64	69	77		75	68	68	77				
June 24	11			80	77	75	76				66	64	70	69			
June 25	12	84	76	83	99	88					129	70	103	80	88	86	
June 26	13	c			110	93								110	102	112	
June 27	14	120			133	110								128	120	135	103
June 28	15	105			120									118	103	113	83
June 29	16	103			121									105	103	116	83
June 30	17				126									114	105	123	80
July 1	18	a[b]			139									118	102	128	97
July 2	19	77			131									115	95	118	88
July 3	20	91			134									126	100	114	88
July 4	21	78			130									117	95	122	100
July 5	22	80			131										108	128	116
July 6	23	69			78									110	85	108	91
July 7	24	72			94									108	86	111	90
July 8	25	85			100									225	96	113	134
July 9	26	83			97											85	102
July 10	27	83			96											88	109
July 11	28	79			101											94	102

Note: Samples showing what we believe to be excess tritium are indicated in bold type. Other, isolated high values are assumed to be caused by sampling errors.

[a]c = electrolyte changed.
[b]a = new cell.

small increase in tritium level was seen after ~30 days from the start. No detectable tritium was found in the electrode at the end of the study.

Cells 41 and 43 also produced minor amounts of tritium. Cell 41 contained ~12 in. of 0.81-mm (0.032-in.)-diam wire[8] that was wound into a spiral. Cell 43 was an alloy of palladium and boron that was made by arc-melting the elements together. Although the tritium content of these cells is small, the amount is significant because the abrupt increase is not consistent with the gradual increase from enrichment. The amount is well outside the uncertainty in counting error, as is demonstrated later. The enrichment phenomenon also is discussed in detail later. The few high, isolated high counting rates were ignored as being possible sampling errors.

Inactive cells running at the same time (26, 27, 28, 31, and 33 through 37), using the same heavy water, gave an average distintegration rate of 154 ± 31 dis/min·ml based on 96 data points shown in Table II. This value is somewhat higher than the tritium level measured later in closed cells because of enrichment in these open cells.

[8]Supplied by J. Marshal, Marshal Laboratories, 5854 Rawhide Court, Suite B, Boulder, Colorado 80302. Detected elements were as follows: silver = 20, aluminum = 35, gold = 115, calcium = 10, iron = 95, platinum = 140, silicon = 40, and zinc = 25 ppm (wt). Undetected elements were As, B, Ba, Be, Bi, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Ga, Gd, Ge, Hf, Hg, Ho, Ir, La, Li, Lu, Mg, Mn, Mo, Nb, Nd, Ni, Os, Pb, Pr, Rb, Re, Rh, Ru, Sb, Sc, Se, Sm, Sn, Tl, Tm, U, V, W, Yb, and Zr (all <10 ppm).

To verify that the high counts in cells 29 and 30 were not caused by chemiluminescence, three procedures were applied:

1. Part of the sample was neutralized, distilled, and counted.
2. The light spectrum[h] was measured and compared to a known tritium sample.
3. The undistilled sample was recounted after sitting a month.

All three procedures were consistent with tritium being present in the samples. A similar result was obtained when sample 30 was counted by another group at Los Alamos National Laboratory.

Data Set 2

Gradually the cells were modified. First, plastic was substituted for glass and then recombiners[a] were added. The recombinate ran back into the cell, and any excess gas left the cell through a small hole. About 16 cells were studied in this way. Examples of the counting rate are shown in Table III.

As can be seen in Fig. 3, where two typical cells are plotted as a function of time, the tritium values were essentially constant as would be expected for inactive closed cells. The line is a least-squares fit to sample 62. The tritium disintegration rates for these inactive cells are listed in Table IV along with the standard deviations. The scatter in these data is useful in evaluating the total random errors associated with counting, with transferring the electrolyte to the scintillator fluid, and with changes in background. An evaluation of these inactive cells indicates an average standard deviation of ±14 dis/min·ml involving a 41-day period, 13 cells, and 446 measurements. However, because a few very high or low points are occasionally seen, claim of tritium production is only based on a consistent pattern of values that is well outside this error. In addition, this data set gives an average value of 138 dis/min·ml as the disintegration rate of tritium in the electrolyte used in this work. During the duration of the studies described in this technical note, approximately thirty 1-ℓ bottles of heavy water[b] were used with no significant difference in tritium activity from this value or between individual bottles.

The background is based on using 1 ml of old well water[i] in place of the electrolyte and counting for 10 min. Data for 100 days are shown as a function of time in Fig. 4. This time interval overlaps data sets 2 and 3. There is no apparent trend with time and the average value is 19.3 ± 2.4 count/min. A rounded value of 20 count/min is used in all calculations.

The absence of any tritium production activity in these

[h]The light spectrum is different when luminescence is caused by beta emission compared to chemical effects.

[i]Very old (>2000 yr) well water is available at Los Alamos and was used because of its very low tritium content.

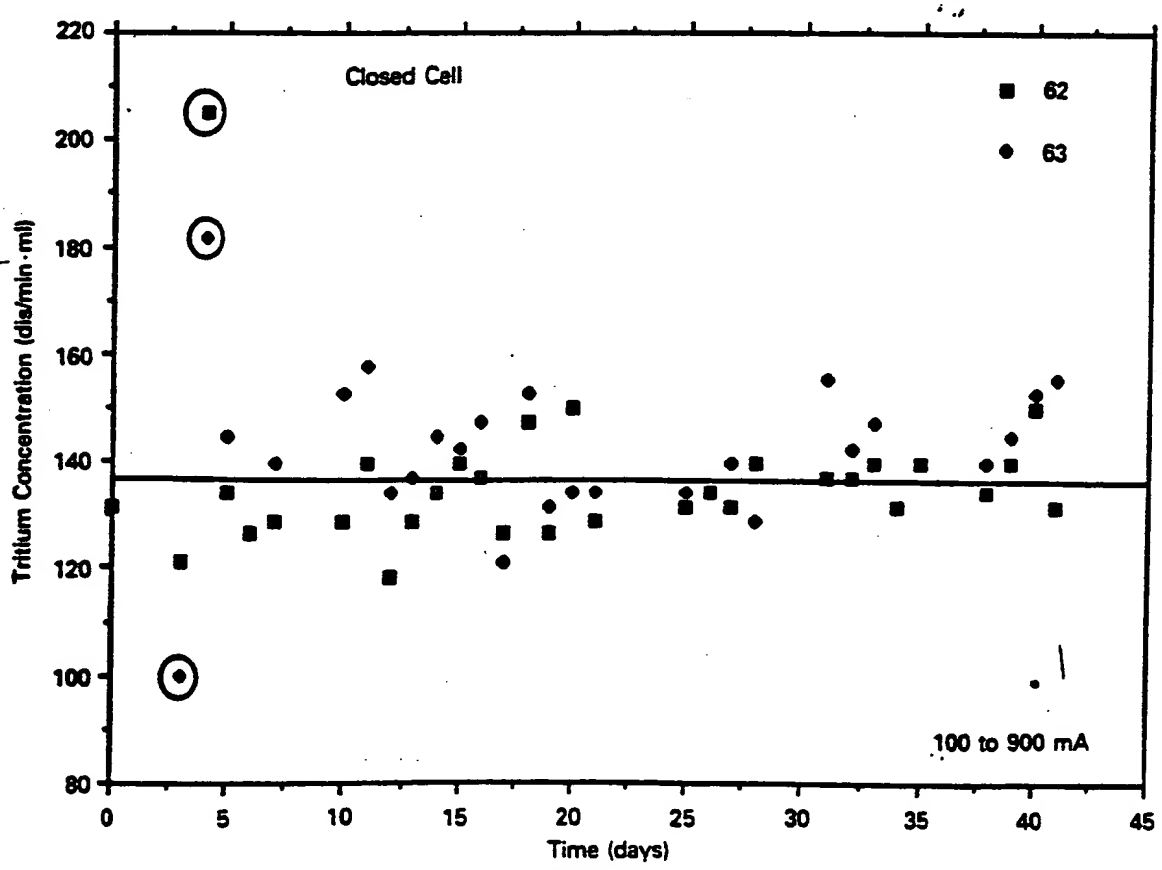

Fig. 3. Example of closed cell behavior. Circled points were eliminated in the data treatment.

TABLE III

Closed Cells Run with Recombiners [gross counting rates (count/min·ml)]
(10-min count using 1 ml of electrolyte)

Date	Day	Cell Number												
		49	51	54	55	56	57	58	59	60	61	62	63	65
		Start =												
		August 15	July 4	July 31	July 31	July 31	August 9	August 9	August 9	August 9	August 9	August 9	August 9	August 15
August 11	0		80	70	70	80	60	70	70	70	70	70	70	
August 14	3		75	71	68	71	79c[a]	65	68	66	66	66	*58*	
August 15	4	78	77	87	80	81	78	78	79	91	82	*98*	*89*	69
August 16	5	65	79	65	67	73	67	68	d[b]	d	67	71	75	73
August 17	6	61	71c	69	69	68	66	65	d	d	68	68	68	67
August 18	7	68	70	70	70	71	70	70	d	d	69	69	73	66
August 21	10	70	72	67	71	71	73	68	d	d	70	69	78	69e[c]
August 22	11	71	72	70	70	65	70	66	*106*	71	70	73	80	68
August 23	12	64	68	72	70	69	80	71	82c	68c	63c	65	71	70
August 24	13	66	71	74	75	68	68	69	61	70	65	69	72	70
August 25	14	71	70	72	67	70	66c	66	70	68	70	71	75	66
August 26	15		82	73	75		81	80	65	70	*56*	73	74	71
August 27	16	60	76	70	71	71	*129*	73	69	73	71	72	76	72
August 28	17	68	73	68	73	72	79	72	72	68	59	68	66	66
August 29	18	67	77	72	75	67	69	74	71	74	72	76	78	69
August 30	19	67	72	73	77	71	94	66	70	75	74	68	70	65
August 31	20	73	83	71	71	69	73	70	73	80	75	77	71	63
September 1	21	66	76	72	75	71	84	68	69	77	68	69	71	66
September 5	25	71	76	72	71	74	84	69	68	70	67	70	71	73
September 6	26	71	75	69	74	73	88	71	69	73	69	71	71	69
September 7	27	68	77	74	79	76	90	74	71	72	70	70	73	66
September 8	28	74	81	73	73	82	90	74	75	76	77	73	69	68
September 11	31	73	79	74	74	75	80	77	76	81	78	72	79	70
September 12	32	69		67	74	73	76	72	67	67	72	72	74	69
September 13	33	72		69	68	76	89	70	72	80	71	73	76	67
September 14	34	*50*		70	70	80	90	80	70	80	70	70	70	70
September 15	35	71		71	71	70	82	74	72	75	70	73	73	64
September 18	38	71		71	76	73	83	75	76	74	75	71	73	70
September 19	39	73		75	68	71	82	70	72	77	75	73	75	68
September 20	40	81		75	74	77	84	67	80	78	73	77	78	65
September 21	41	67		68	72	76	78	70	73	72	71	70	79	70
September 26	46	82R[d]					86R				85R	79R		70R

Note: Values in italic were eliminated in the data treatment.

[a]c = new electrolyte.
[b]d = low count because of suspended black nickel oxide.
[c]e = gas recombination explosion.
[d]R = after current reverse.

cells suggests that the plastic container or the recombiner material added something to the electrolyte that inhibited the reaction. Consequently, future cells were made of glass and were designed so that the recombinate did not flow back into the cell. This design allowed the tritium content of the gas to be determined, and, from this information, the distribution ratio of tritium between liquid and gas could be calculated.

Data Set 3

The latest group of cells have the design shown in Fig. 5. Here, the recombinate is collected in a plastic intravenous (IV) bag. The cell is a glass jar containing 120 ml of fluid, and the anodes are either platinum gauze or nickel wire. In each case, there is a minimum distance of ~5 mm between the anode and cathode. Parafilm was wrapped around the jar to seal the lid, a glass tube protected the lead from electrolytic attack, and Torr Seal was applied where the leads passed through the lid. A hypodermic needle was used to attach the IV system to the cell. Thus, stainless steel was in the cell in addition to 0.2 *N* LiOD and the anode material. A small silicone rubber disk was placed, in some cases, on the end of the cathode to prevent shorting to the anode.

TABLE IV

Tritium Disintegration Rate and Standard Deviation for Inactive Cells in Data Set 2

Cell Number	dis/min·ml	Number of Values
49	128 ± 15	28
51	146 ± 11	23
54	134 ± 10	38
55	137 ± 12	38
56	138 ± 12	36
57	154 ± 23	30
58	134 ± 11	31
59	136 ± 12	26
60	142 ± 14	27
61	132 ± 14	31
62	134 ± 7	30
63	141 ± 9	29
65	127 ± 7	28

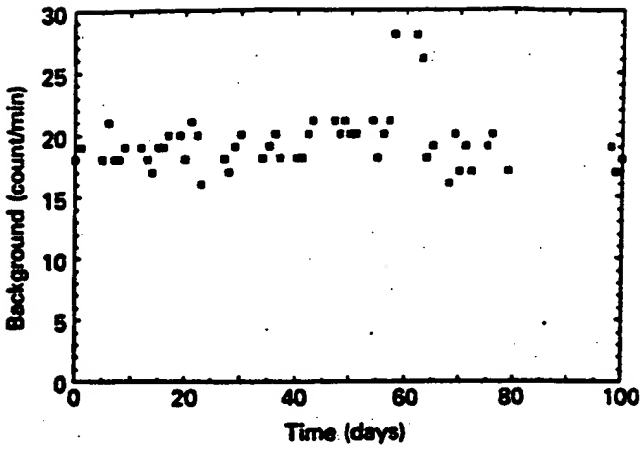

Fig. 4. Counting background during time interval of data sets 2 and 3 based on 1 ml of tritium-free water.

Seven of the 9 cells that were started at the same time and were running in series at constant current[j] showed evidence of tritium production. Two were apparently inactive. The design details of this group are shown in Table V, and the counting rates are listed in Table VI.

Two cells, 70 and 79, used cathodes made from 1.0-mm wire.[k] Both used a nickel wire anode, but 79 had a small piece of silver attached. Cells 71 to 78 had palladium cathodes cut as a 1-mm strip from a 1.3-mm-thick sheet.[l] All of the strips except one (78) were heated in paraffin vapor. A few

[j]The power supplies were Hewlett-Packard 6038A.
[k]Supplied by Professor Martin, Texas A&M University.
[l]Purchased from Englehard Company.

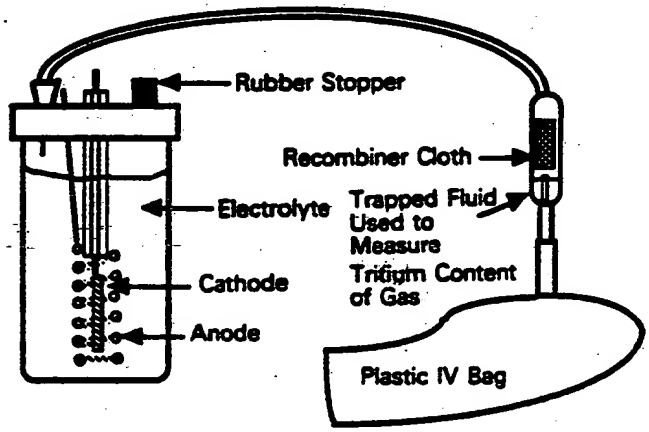

Fig. 5. Cell design 5.

TABLE V

Materials Used in Cells 70 to 79

Cell Number	Shape	Surface Treatment	Method	Anode	Excess Tritium	D/Pd
70	Wire	None	HNO_3[a]	Ni + S[b] wire	No	
71	Strip	C(0.0001*g*)-S(0.0013*g*)	Paraffin, H_2S	Platinum gauze	Yes	>0.55
72	Strip	C(0.0001*g*)-S(0.0000*g*)	Paraffin, H_2S	Platinum gauze	Yes	0.81
73	Strip	C(0.0002*g*)	Paraffin	Nickel wire	Yes	0.81
74	Strip	C(0.0003*g*)	Paraffin	Ni + S wire	No	0.78
75	Strip	C(0.0001*g*)-S(0.0000*g*)	Paraffin, H_2S	Platinum gauze	Yes	0.71
77	Strip	C(0.0002*g*)-S(0.0004*g*)	Paraffin, H_2S	Platinum gauze	Yes	0.69
78	Strip	None	HNO_3	Ni + S wire	Yes	0.79
79	Wire	None	HNO_3	Nickel wire + silver[c]	Yes	<0.94

Note: All electrode areas = ≈1.3 cm^2 and all cells are glass.

[a]Cleaned with dilute HNO_3.
[b]Nickel wire heated in H_2S.
[c]A small piece of silver is attached to the nickel wire.

TABLE VI

Gross Count/min·ml Obtained from Cells 70 to 79

(Recombinate counting rates are identified with a *g*.)

Date	70	70g	71	71g	72	72g	73	73g	74	74g	75	75g	77	77g	78	78g	79	79g
September 5	Start																	
September 6									Start		Start		Start		Start		Start	
September 7	64		Start		Start		Start		59		69		84		75		67	
September 8	79				74				57		66				83		89	
September 11	62		87		56		60				90		80		84		88	
September 12	64		99		80		77				94		56		86		86	
September 13	60		80		86		85		58									
September 14	70	80	100	100	90	80	100	100	70	60	100	100	90	100	90	80	100	100
September 15	73		106		97		110		73		101		113		109		103	
September 18	73		129		95		135		63		123		122		98		109	
September 19	65		116		89		128		67		119		122		106		107	
September 20	67		116		97		135		72		128		123		107		112	
September 21	71	62	109	106	93	90	122	93	70	77	119	115	117	96	105	93	101	91
September 22	74		116		105		133		72		122		121		108		112	
September 25	77		118		107		147		67		124		131		120		130	
September 26	77	63	121	98	106	87	145	121	68	73	129	107	117	101	113	96	119	93
September 27	77		121		108		153		74		120		126		120		121	
September 28	83		128		115		164		78		126		133		124		127	
September 29	76	69	118	91	106	90	144	102	72	75	129	110	133	90	124	100	126	99
October 2	86	78	132	99	107	88	147	122	85	75	136	119	123	124	141	132	122	
October 3	79		113		121		167		77		148		123		123		127	
October 4	82	75	121	110	118	95	165	117	76	97	150	124	132	108	129	100	125	
October 5	84		126		115		151		83		151		131		130		136	
October 6	78	80	115	106	106	98	124	107	80	84	122	115	122	144	115	115	118	
October 10	78		111	110	108	92	123	105	81	108	116	128	116	103	111	101	119	
October 11	78		117		107		130		81		112		133		112		116	
October 12	84		118		103		118		80		123		116		108		112	
October 13	81	76	118	103	109	99	116	114	76	77	115	102	118	94	104	102	115	
October 16	82	80	111	89	111	93	118	99	77	80	116	106	116	93	115	96	113	
October 17	76		120		113		110		81		114		115		108		108	
October 18	77		110		107		111		83		118		121		109		106	
October 19	80		116		106		104		81		115		121		109		109	
October 20	82	68	111	90	111	83		85		79	123	88	113	89	111	87	109	90
October 23	83	71	110	89	105	80	116	83	75	82	114	92	115	93	109	81	96	83
October 24	86		106		106		105		79		110		112		106		97	
October 27	79		113		115		110		79		114		116		109		96	
November 3	90	74	116	98	121	98	114	99	84	75	130	99	119	98	105	105	100	91
November 6	84	91	111	91	107	90	105	82	75	95	117	106	117	106	106	101	92	88
November 7	84		109		109		108		75		107		120		107		90	
November 9	80	92	107	108	104	98	105	100	76	91	111	111	110	112	103	103	89	87
November 13	103	80	109	101	109	91	105	106	73	86	102	102	117	90	103	93	87	89
November 15	90		102		107		105		73		106		115		106		90	
November 17	87		109		110		95		74		106		119		109		88	

Note: The gas samples are based on 0.5 ml of recombinate and, therefore, have a larger uncertainty (±0.02 ml) than the electrolyte (±0.01 ml), which is based on 1 ml.

were subsequently heated in H_2S. Although the temperatures and times were arbitrary, a weight increase caused by interaction with the paraffin and H_2S was noted. This weight change is noted in Table V. At the end of the study, the cathodes were weighed to determine the deuterium content, and the listed D/Pd ratios were calculated. The cathode in cell 71 showed a nonuniform surface discoloration, and cell 79 had a heavy, dark surface covering that was probably silver.

Cells 71, 72, 75, and 77 had an anode made from platinum gauze that was formed into a 1-cm-diam tube. The nickel anode in cells 70, 74, and 78 was heated in H_2S before use.

Periodically, 0.5 ml of fluid was removed from the region below the recombiner in the IV drip system where ~1 ml of recombinate was trapped. This was analyzed for tritium and is designated with a *g* in Table VI.

Cells 70 and 74 showed no detectable excess tritium. Nevertheless, the two inactive cells had a slow, similar increase in tritium content[f] due to enrichment,[14] as can be seen in Fig. 6. This contrasts with the closed cell behavior seen

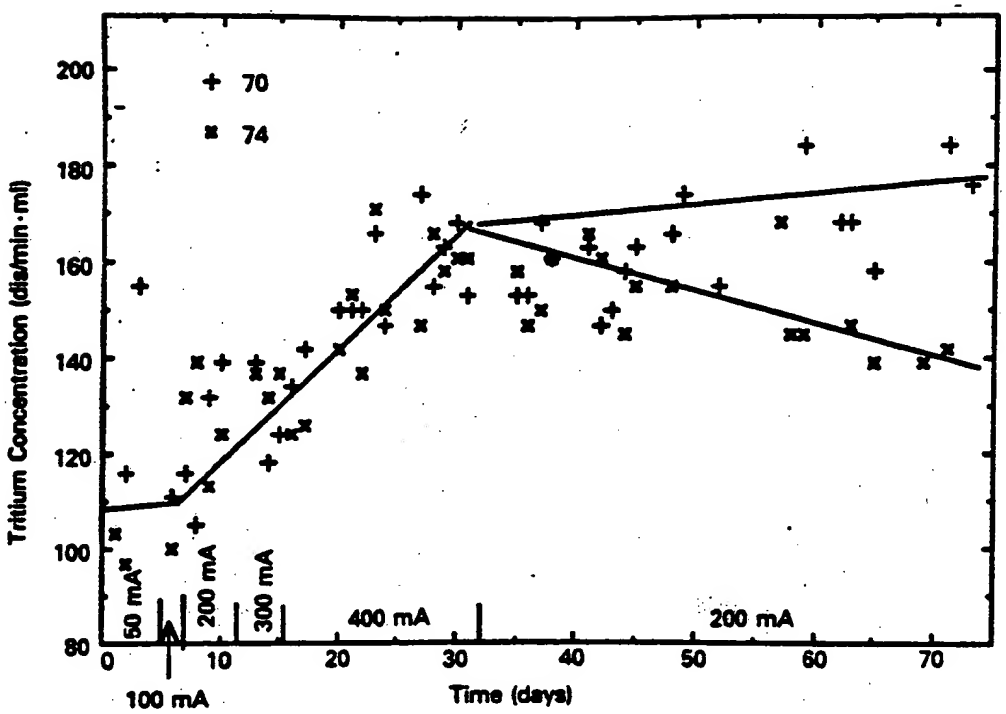

Fig. 6. Time variation of the tritium concentration in inactive cells.

in Fig. 3. During the first 30 days, the distribution ratio of both cells appears to be independent of time and current within the scatter of the data. After the current was reduced at day 31, cell 74 began losing tritium preferentially into the gas. Cell 70 continued to show an expected increase in tritium content. The average distribution ratio (gas/liquid) for cell 74 is 1.12 ± 0.17 (13 data sets) compared to a value of 0.91 ± 0.16 (15 data sets) for cell 70. These values are rather uncertain because the gas samples are based on only 0.5 ml of fluid taken using a hypodermic syringe rather than a calibrated pipette. Consequently, only the trend to a higher value for cell 74 compared to cell 70 can be accepted.

The scatter in counting rate for the electrolytic samples, which is approximately ±5 count/min·ml (±14 dis/min·ml), is caused by the sum of errors in sampling, counting, and changes in background. This value is consistent with the behavior of data set 2, as described previously.

The cells that have produced tritium are compared in Fig. 7. There is a range of values, but each exceeded the count rate of the inactive cells after ~2 to 3 days and continued to increase in steps. Several of the cells have shown especially interesting behavior. Two most active cells (73 and 75) are compared to an inactive cell (70) in Fig. 8. The scatter of values for the active cells is larger than that found for inactive cells, indicating possible production of tritium bursts. In general, the recombinate followed the count rate of the electrolyte but had a smaller value. Thus, there is no indication that significant tritium has left the cell by means of the gas phase, in contrast to the experience at Texas A&M University[7] where much higher production rates were observed. Occasionally, slightly more tritium is found in the recombinate than in the liquid such as on October 6 in cell 77 or on October 10 in cell 75. These values might have resulted because of short tritium bursts before the sample was taken or because of sampling errors. The absence of a pattern caused us to ignore such values.

It is interesting that all the cells that produced tritium appeared to start and stop production at approximately the same time. Once tritium production stopped, the amount of tritium appeared to decrease over several days to a constant value that is significantly above that shown by inactive cells.

Several cells containing 0.2 *N* LiOH (normal water electrolyte), a palladium cathode, and a nickel anode have been studied recently for up to 30 days with no increase in tritium concentration. Although this is a relatively short time, it is longer than is necessary to produce tritium in D_2O cells that become active. Such water cells will be included in future work.

DISCUSSION

Production of excess tritium in cells 71, 72, 73, 75, 77, 78, and 79 is evident in the data shown in Fig. 7 where a comparison is made for the two inactive cells. To determine the magnitude of this excess, the effect of enrichment must be subtracted. Based on measurements of tritium in the gas and electrolyte of cells 70, 73, 74, and 75, a distribution ratio of 0.84 was chosen to calculate the excess tritium in cell 73. This calculation shows that more tritium was found in cell 73 than was present initially or was in the D_2O that was added as electrolyte replacement.

The distribution ratio in this study is defined as the tritium concentration of the gas divided by the tritium concentration of the liquid. A value less than unity is calculated when the tritium content of the liquid increases while a value greater than unity results when tritium is preferentially lost by the liquid.

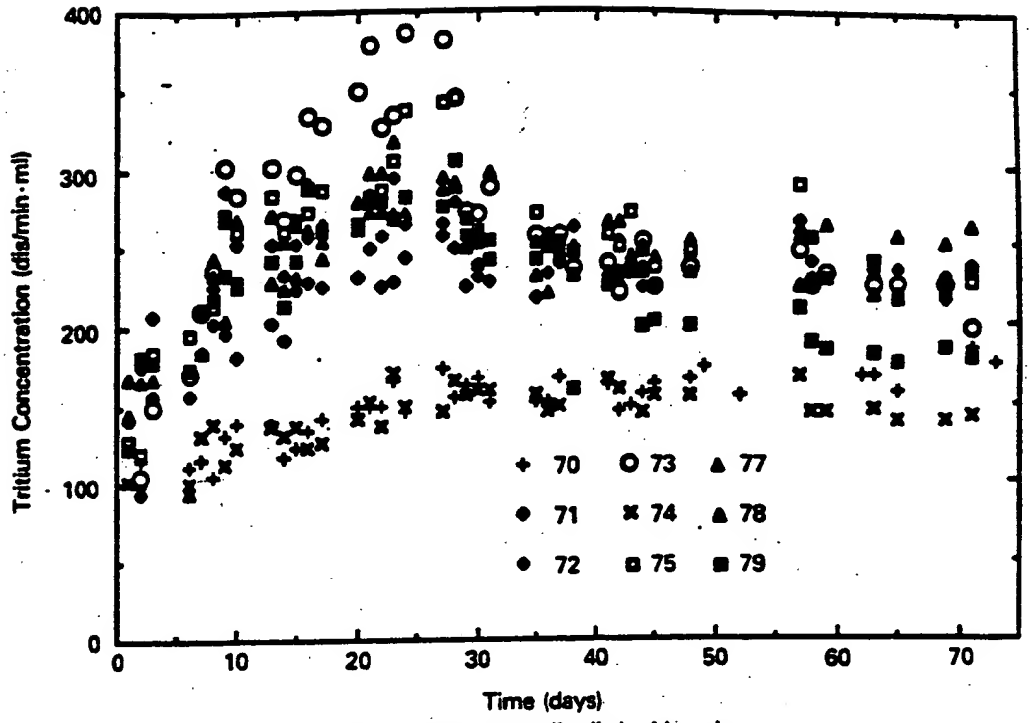

Fig. 7. Comparison among all cells in this series.

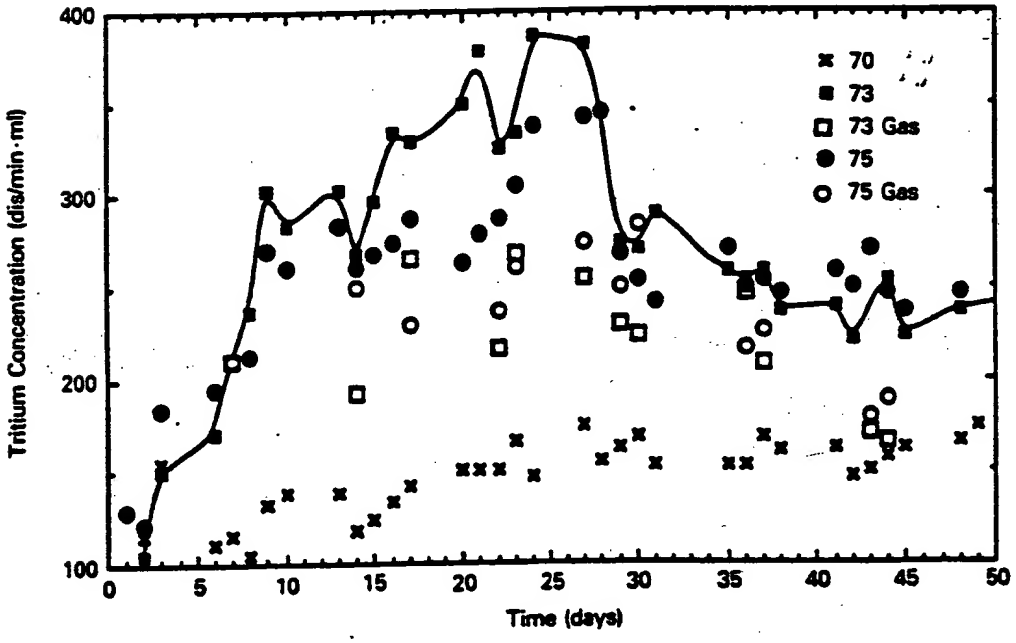

Fig. 8. Tritium counts for two active cells and one inactive cell. The tritium activity in the recombinate is shown as open symbols.

The excess tritium is determined by taking the initial tritium content, subtracting the tritium lost to the gas phase due to electrolysis, and adding the amount used to replace that volume lost by the cell.[m] The excess is the difference between the resulting value and the measured amount of tritium determined daily. Table VII lists the daily inventory of tritium

[m]We added 1 ml of electrolyte, to replace that taken during sampling, and D_2O, to replace that lost due to electrolysis, on a daily basis, generally before the tritium sample was taken. Because the cell contained 120 ml of electrolyte and the electrolysis rate was generally low, these periodic additions of fluid had only a small perturbation on the tritium concentration.

TABLE VII

Tritium Inventory and Excess Calculated for Cells 70 and 73 Using a Distribution Ratio of 0.84

1	2	3	4	5	6	7	8	9	10	11
Day	Gross Counting Rate (count/min)	Net Decomposition Rate (dis/min)	I (mA)	D_2O (ml/day)	Sum D_2O	Added Tritium (mol)	Lost Tritium (mol)	Tritium Present (mol)	Excess Tritium (mol)	Fraction Tritium
Cell 70										
0		150	50	0.00	0.0	0.0E+00[a]	0.0E+00	2.8E−13		
1		150	50	0.41	0.4	9.5E−16	7.9E−16	2.8E−13	−1.5E−16	−0.00
2	76	147	50	0.41	0.8	4.2E−15	3.9E−15	2.7E−13	−5.3E−15	−0.02
3	79	155	50	0.41	1.2	7.5E−15	7.1E−15	2.9E−13	9.4E−15	0.03
4		150	50	0.41	1.6	8.4E−15	7.9E−15			
5		150	50	0.41	2.0	9.4E−15	8.7E−15			
6	62	111	50	0.41	2.4	1.3E−14	1.1E−14	2.1E−13	−7.5E−14	−0.27
7	64	116	50	0.41	2.8	1.6E−14	1.3E−14	2.2E−13	−6.6E−14	−0.24
8	60	105	50	0.41	3.3	1.9E−14	1.6E−14	2.0E−13	−8.7E−14	−0.31
9	70	132	100	0.81	4.1	2.3E−14	1.9E−14	2.4E−13	−3.9E−14	−0.14
10	73	139	200	1.63	5.7	3.0E−14	2.4E−14	2.6E−13	−2.5E−14	−0.09
11		140	200	1.63	7.3	3.3E−14	2.7E−14			
12		140	200	1.63	9.0	3.7E−14	3.0E−14			
13	73	139	200	1.63	10.6	4.3E−14	3.5E−14	2.6E−13	−2.8E−14	−0.10
14	65	118	200	1.63	12.2	4.9E−14	4.0E−14	2.2E−13	−6.9E−14	−0.25
15	67	124	200	1.63	13.8	5.5E−14	4.4E−14	2.3E−13	−6.0E−14	−0.22
16	71	134	200	1.63	15.5	6.2E−14	4.9E−14	2.5E−13	−4.2E−14	−0.15
17	74	142	300	2.44	17.9	7.0E−14	5.6E−14	2.6E−13	−2.9E−14	−0.10
18		140	300	2.44	20.3	7.5E−14	6.0E−14			
19		150	300	2.44	22.8	8.1E−14	6.5E−14			
20	77	150	300	2.44	25.2	8.9E−14	7.2E−14	2.8E−13	−1.7E−14	−0.06
21	77	150	300	2.44	27.7	9.7E−14	7.9E−14	2.8E−13	−1.8E−14	−0.06
22	77	150	400	3.26	30.9	1.1E−13	8.8E−14	2.8E−13	−1.9E−14	−0.07
23	83	166	400	3.26	34.2	1.2E−13	9.7E−14	3.1E−13	1.0E−14	0.04
24	76	147	400	3.26	37.4	1.3E−13	1.1E−13	2.7E−13	−2.6E−14	−0.09
25		150	400	3.26	40.7	1.3E−13	1.1E−13			
26		160	400	3.26	44.0	1.4E−13	1.2E−13			
27	86	174	400	3.26	47.2	1.5E−13	1.3E−13	3.2E−13	2.2E−14	0.08
28	79	155	400	3.26	50.5	1.6E−13	1.4E−13	2.9E−13	−1.4E−14	−0.05
29	82	163	400	3.26	53.7	1.7E−13	1.5E−13	3.0E−13	6.3E−16	0.00
30	84	168	400	3.26	57.0	1.8E−13	1.6E−13	3.1E−13	1.0E−14	0.04
31	78	153	400	3.26	60.2	1.9E−13	1.7E−13	2.8E−13	−2.0E−14	−0.07
32		150	400	3.26	63.5	2.0E−13	1.7E−13			
33		150	400	3.26	66.7	2.1E−13	1.8E−13			
34		150	400	3.26	70.0	2.1E−13	1.9E−13			
35	78	153	400	3.26	73.3	2.2E−13	1.9E−13	2.8E−13	−2.5E−14	−0.09
36	78	153	400	3.26	76.5	2.3E−13	2.0E−13	2.8E−13	−2.6E−14	−0.09
37	84	168	200	1.63	78.1	2.4E−14	2.1E−13	3.1E−13	3.5E−15	0.01
38	81	161	200	1.63	79.8	2.5E−13	2.1E−13	3.0E−13	−1.1E−14	−0.04
39		160	200	1.63	81.4	2.5E−13	2.2E−13			
40		160	200	1.63	83.0	2.5E−13	2.2E−13			
41	82	163	200	1.63	84.7	2.6E−13	2.3E−13	3.0E−13	−7.4E−15	−0.03
42	76	147	200	1.63	86.3	2.7E−13	2.3E−13	2.7E−13	−3.7E−14	−0.13
43	77	150	200	1.63	87.9	2.7E−13	2.4E−13	2.8E−13	−3.3E−14	−0.12
44	80	158	200	1.63	89.5	2.8E−13	2.4E−13	2.9E−13	−1.9E−14	−0.07
45	82	163	200	1.63	91.2	2.8E−13	2.5E−13	3.0E−13	−9.1E−15	−0.03
46	83	166	200	1.63	92.8	2.9E−13	2.6E−13	3.1E−13	−4.3E−15	−0.02
47	86	174	200	1.63	94.4	3.0E−13	2.6E−13	3.2E−13	1.1E−14	0.04
48		160	200	1.63	96.0	3.0E−13	2.7E−13			
49		160	200	1.63	97.7	3.0E−13	2.7E−13			
50	79	155	200	1.63	99.3	3.1E−13	2.8E−13	2.9E−13	−2.5E−14	−0.09

See footnotes at end of table.

(Continued)

TABLE VII (Continued)

1	2	3	4	5	6	7	8	9	10	11
Day	Gross Counting Rate (count/min)	Net Decomposition Rate (dis/min)	I (mA)	D_2O (ml/day)	Sum D_2O	Added Tritium (mol)	Lost Tritium (mol)	Tritium Present (mol)	Excess Tritium (mol)	Fraction Tritium
Cell 70 (Continued)										
51		160	200	1.63	100.9	3.1E−13	2.8E−13			
52		170	200	1.63	102.6	3.2E−13	2.8E−13			
53		170	200	1.63	104.2	3.2E−13	2.9E−13			
54		170	200	1.63	105.8	3.3E−13	2.9E−13			
55		180	200	1.63	107.4	3.3E−13	2.9E−13			
56		180	200	1.63	109.1	3.3E−13	3.0E−13			
57	90	184	200	1.63	110.7	3.4E−13	3.0E−13	3.4E−13	2.9E−14	0.10
58		170	200	1.63	112.3	3.4E−13	3.1E−13			
59		170	200	1.63	114.0	3.5E−13	3.1E−13			
60	84	168	200	1.63	115.6	3.5E−13	3.2E−13	3.1E−13	−8.2E−16	0.00
61	84	168	200	1.63	117.2	3.6E−13	3.2E−13	3.1E−13	−7.5E−16	0.00
62		160	200	1.63	118.8	3.6E−13	3.3E−13			
63	80	158	200	1.63	120.5	3.7E−13	3.3E−13	2.9E−13	−2.1E−14	−0.08
64		170	200	1.63	122.1	3.7E−13	3.4E−13			
65		170	200	1.63	123.7	3.8E−13	3.4E−13			
66		170	200	1.63	125.3	3.8E−13	3.4E−13			
67	103	218	200	1.63	127.0	3.9E−13	3.5E−13	4.1E−13	9.3E−14	0.33
68		200	200	1.63	128.6	3.9E−13	3.6E−13			
69	90	184	200	1.63	130.2	4.0E−13	3.6E−13	3.4E−13	3.0E−14	0.11
70		180	200	1.63	131.9	4.0E−13	3.7E−13			
71	87	176	200	1.63	133.5	4.1E−13	3.7E−13	3.3E−13	1.6E−14	0.06
Cell 73										
0		147	50	0.00	0.0	0.0E+00	0.0E+00	2.7E−13		0.00
1		150	50	0.41	0.4	9.5E−16	7.9E−16			
2	66	121	50	0.41	0.8	4.2E−15	3.3E−15	2.3E−13	−4.9E−14	−0.18
3	77	150	100	0.81	1.6	8.4E−15	7.2E−15	2.8E−13	4.4E−15	0.02
4	85	171	200	1.63	3.3	1.5E−14	1.4E−14	3.2E−13	4.4E−14	0.16
5	100	211	200	1.63	4.9	2.1E−14	2.1E−14	3.9E−13	1.2E−13	0.43
6	110	237	200	1.63	6.5	2.7E−14	3.0E−14	4.4E−13	1.7E−13	0.62
7		300	200	1.63	8.1	3.1E−14	3.6E−14			
8		300	200	1.63	9.8	3.4E−14	4.3E−14			
9	135	303	200	1.63	11.4	4.0E−14	5.4E−14	5.6E−13	3.0E−13	1.11
10	128	284	200	1.63	13.0	4.7E−14	6.4E−14	5.3E−13	2.7E−13	1.00
11	135	303	300	2.44	15.5	5.5E−14	7.8E−14	5.6E−13	3.1E−13	1.15
12	122	268	300	2.44	17.9	6.3E−14	9.1E−14	5.0E−13	2.5E−13	0.93
13	133	297	300	2.44	20.3	7.1E−14	1.1E−13	5.5E−13	3.1E−13	1.15
14		300	300	2.44	22.8	7.6E−14	1.1E−13			
15		300	300	2.44	25.2	8.2E−14	1.2E−13			
16	147	334	400	3.26	28.5	9.2E−14	1.4E−13	6.2E−13	4.0E−13	1.46
17	145	329	400	3.26	31.7	1.0E−13	1.6E−13	6.1E−13	4.0E−13	1.46
18	153	350	400	3.26	35.0	1.1E−13	1.8E−13	6.5E−13	4.5E−13	1.64
19	164	379	400	3.26	38.3	1.2E−13	2.0E−13	7.0E−13	5.1E−13	1.88
20	144	326	400	3.26	41.5	1.3E−13	2.2E−13	6.1E−13	4.3E−13	1.56
21		330	400	3.26	44.8	1.4E−13	2.4E−13			
22		330	400	3.26	48.0	1.5E−13	2.5E−13			
23	147	334	400	3.26	51.3	1.6E−13	2.7E−13	6.2E−13	4.6E−13	1.69
24	167	387	400	3.26	54.5	1.7E−13	2.9E−13	7.2E−13	5.7E−13	2.10
25	165	382	400	3.26	57.8	1.8E−13	3.2E−13	7.1E−13	5.8E−13	2.11
26	151	345	400	3.26	61.0	1.9E−13	3.4E−13	6.4E−13	5.2E−13	1.89
27	124	274	400	3.26	64.3	2.0E−13	3.5E−13	5.1E−13	3.9E−13	1.43
28		275	400	3.26	67.6	2.0E−13	3.6E−13			
29		275	400	3.26	70.8	2.1E−13	3.7E−13			

(Continued)

TABLE VII (Continued)

1	2	3	4	5	6	7	8	9	10	11
Day	Gross Counting Rate (count/min)	Net Decomposition Rate (dis/min)	I (mA)	D_2O (ml/day)	Sum D_2O	Added Tritium (mol)	Lost Tritium (mol)	Tritium Present (mol)	Excess Tritium (mol)	Fraction Tritium
Cell 73 (Continued)										
30		275	400	3.26	74.1	2.2E−13	3.9E−13			
31	123	271	200	1.63	75.7	2.2E−13	4.0E−13	5.0E−13	4.0E−13	1.47
32	130	289	200	1.63	77.3	2.3E−13	4.1E−13	5.4E−13	4.4E−13	1.61
33	118	258	200	1.63	79.0	2.4E−13	4.2E−13	4.8E−13	3.9E−13	1.41
34	116	253	200	1.63	80.6	2.4E−13	4.3E−13	4.7E−13	3.8E−13	1.39
35		250	200	1.63	82.2	2.5E−13	4.3E−13			
36		250	200	1.63	83.8	2.5E−13	4.4E−13			
37	118	258	200	1.63	85.5	2.6E−13	4.5E−13	4.8E−13	4.0E−13	1.45
38	110	237	200	1.63	87.1	2.6E−13	4.5E−13	4.4E−13	3.6E−13	1.31
39	111	239	200	1.63	88.7	2.7E−13	4.6E−13	4.5E−13	3.7E−13	1.34
40	104	221	200	1.63	90.3	2.8E−13	4.7E−13	4.1E−13	3.3E−13	1.22
41		230	200	1.63	92.0	2.8E−13	4.8E−13			
42		230	200	1.63	93.6	2.8E−13	4.8E−13			
43		240	200	1.63	95.2	2.9E−13	4.9E−13			
44	116	253	200	1.63	96.9	2.9E−13	5.0E−13	4.7E−13	4.0E−13	1.46
45	105	224	200	1.63	98.5	3.0E−13	5.0E−13	4.2E−13	3.5E−13	1.27
46		230	200	1.63	100.1	3.0E−13	5.1E−13			
47		230	200	1.63	101.7	3.1E−13	5.1E−13			
48	110	237	200	1.63	103.4	3.1E−13	5.2E−13	4.4E−13	3.8E−13	1.38
49		240	200	1.63	105.0	3.2E−13	5.3E−13			
50		240	200	1.63	106.6	3.2E−13	5.3E−13			
51		240	200	1.63	108.3	3.2E−13	5.4E−13			
52		240	200	1.63	109.9	3.3E−13	5.4E−13			
53		240	200	1.63	111.5	3.3E−13	5.5E−13			
54		240	200	1.63	113.1	3.4E−13	5.5E−13			
55	114	247	200	1.63	114.8	3.4E−13	5.6E−13	4.6E−13	4.1E−13	1.49
56		230	200	1.63	116.4	3.5E−13	5.7E−13			
57		230	200	1.63	118.0	3.5E−13	5.7E−13			
58	105	224	200	1.63	119.6	3.5E−13	5.8E−13	4.2E−13	3.7E−13	1.34
59	108	232	200	1.63	121.3	3.6E−13	5.9E−13	4.3E−13	3.8E−13	1.41
60		230	200	1.63	122.9	3.6E−13	5.9E−13			
61	105	224	200	1.63	124.5	3.7E−13	6.0E−13	4.2E−13	3.7E−13	1.36
62		220	200	1.63	126.2	3.7E−13	6.1E−13			
63		220	200	1.63	127.8	3.8E−13	6.1E−13			
64		220	200	1.63	129.4	3.8E−13	6.2E−13			
65	105	224	200	1.63	131.0	3.9E−13	6.2E−13	4.2E−13	3.8E−13	1.38
66		225	200	1.63	132.7	3.9E−13	6.3E−13			
67	105	224	200	1.63	134.3	4.0E−13	6.4E−13	4.2E−13	3.8E−13	1.39
68		225	200	1.63	135.9	4.0E−13	6.4E−13			
69	95	197	200	1.63	137.6	4.1E−13	6.5E−13	3.7E−13	3.3E−13	1.22

Note: Estimated values are shown in bold type. The following values were used in the calculation:

1.55×10^{-17} mol T = 1 dis/min, (1)

Fresh electrolyte = 2.3×10^{-15} mol T/ml, (2)

Density D_2O = 1.1 g/ml, (3)

Tritium half-life = 12.3 yr (4)

and

Mol deuterium/day lost owing to electrolysis = 86.4 I/96 500, where I is the cell current (mA) (5).

[a]Read as $0.0 \times 10^{+0}$.

in cells 70 and 73. The gross counting rate, shown in column 2, includes a background of 20 count/min·ml. Column 3 shows the net decomposition rate that is calculated by subtracting 20 from the value in column 2 and dividing by the detection efficiency, 0.38. Estimated values of net decomposition rates are shown in bold type for days when no measurement was made, generally holidays. The uncertainty in these estimates has a negligible effect on the final result. Electrolytic action, due to the current shown in column 4, caused D_2O to be lost. The daily amount and running sum are shown in columns 5 and 6, respectively. The value is calculated using Eq. (5) at the end of the table. This lost D_2O contains less tritium than does the electrolyte because it was produced from the gas. The tritium concentration of this electrolyzed liquid (hence the gas) is calculated by multiplying the distribution ratio by the tritium concentration of the electrolyte. The volume of this electrolyzed D_2O plus that needed to replace the sampling volume (1 ml on days when a sample was taken) was added to the cell. The amount of added tritium is calculated from its known concentration in the fresh D_2O using the factor listed at the end of the table [Eq. (2)]. A running sum of the added tritium is listed in column 7. The excess shown in column 10 is calculated by adding the value in column 7 to the initial tritium content of the cell, subtracting the amount lost (column 8), and subtracting the result from the measured daily value in column 9. These data are also given as fraction increase, shown in column 11. This quantity is obtained by dividing the excess tritium value for each day by the excess present on the first day.

Cell 70 shows no sign of excess tritium production and is used to determine the distribution ratio. A value of 0.84 produces a minimum in the square of the excess tritium value for data taken over 71 days. Thus, by using this value, the calculated excess tritium value fluctuates around zero with a minimum standard deviation. The distribution ratio can also be obtained by comparing the tritium content in the cell to that found in the recombinate. The average gas/liquid ratio based on 15 data sets is 0.91 ± 0.16. Thus, the distribution ratio can be calculated using two independent methods that give similar results. A distribution value of 0.84 was used to calculate the behavior of cell 73.

Cell 73 was the most active of the seven active cells. Tritium production started after 2 days and continued off and on for ~22 days with evidence of bursts, as can be seen in Fig. 9. The tritium content of the recombinate was less than the electrolyte and gave a somewhat lower distribution ratio (0.82 ± 0.12) than that obtained from cell 70. This difference is within the uncertainty in the measurement. Thus, the excess tritium calculated for this cell is not caused by an unusually small distribution ratio compared to the inactive cell.

The decrease in tritium content after the second burst is significant because workers at Texas A&M Uniersity[15] have seen the same phenomenon. We believe that part of the tritium was produced on the electrode as deuterium-tritium (D-T) gas and part exchanged with deuterium in D_2O. The D-T gas was produced at such a low rate that most of it was able to dissolve in the electrolyte from the gas bubbles, thereby replacing D_2 in the saturated solution. When tritium production stopped, the dissolved D-T gas was gradually flushed out of solution (replaced) by the steady electrolytic production of D_2 gas. This reduction is seen clearly after the 22nd day where the tritium excess shows an exponential drop that approaches a constant value of 1.4. Thus, approximately one-third of the tritium contained in the cell on the 22nd day apparently had been present as dissolved D-T and about two-thirds had exchanged with deuterium in D_2O and remained fixed in the liquid. The other active cells had a different proportion between these two chemical forms.

It is interesting and perhaps significant that these cells all started and stopped producing tritium at approximately the same time. The deposition of surface impurity might have been similar and may account for the similar behavior. This

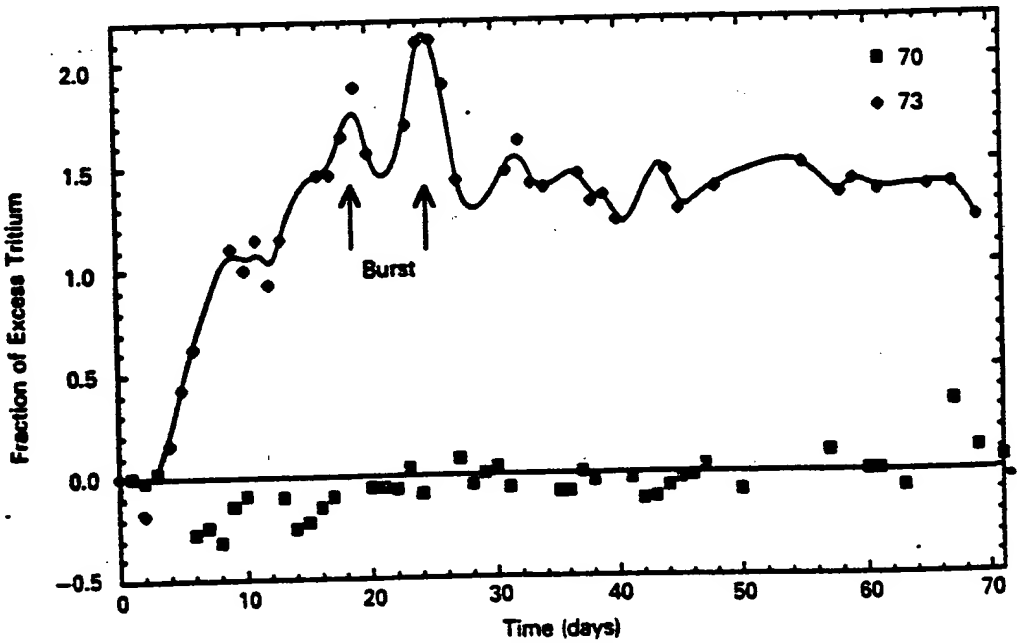

Fig. 9. Fraction excess tritium in cells 70 and 73 using a distribution ratio of 0.84.

possibility will be explored in the future. No clear pattern could be found in the cell designs that gives an explanation for a significant probability for reproducing the behavior. However, cathodes treated with paraffin appear to have a higher probability of success than those not treated this way.

The possibility that tritium could result from contamination of the materials used in the cells is not supported because materials from the same chemical lots were used in cells that did not show the presence of tritium. Twenty other cells, running at the time tritium was being produced in the seven active cells, showed no excess tritium. In addition, these cells were completely sealed so that no external tritium could enter.

The possibility that the recorded counts were caused by chemiluminescence due to active chemical species is not realistic. First, the light spectrum emitted by the scintillator fluid is characteristic of tritium, which, because it has an unusually low energy, cannot be confused with other radioactive materials or with chemiluminescence. Second, the count rate becomes independent of time ~20 min after the scintillator fluid and the electrolyte are mixed, indicating that chemical effects are short-lived in the scintillator fluid used in this work.[a] Counts were recorded only after this effect had died away. Third, the eventual reduction in activity within the cell over a period of time after the second burst (Fig. 9) is only consistent with the source of activity being removed from the cell, not added as would be expected if active chemical species were being produced.

Although the amount of tritium made in this study is small, it is well outside of the uncertainty in the measurement based on a large and consistent data base. The standard deviations for the various data sets are compared in Table VIII. Evidence of tritium production is based on samples having excess tritium between 5 and 785 times the standard deviation based on a total of all random errors. In addition, the pattern of tritium behavior with respect to distribution and exchange is consistent with its known characteristics. Occasional, isolated high values occurred. They were ignored as being possible sampling errors.

It is evident that tritium production in these cells is still very inefficient and probably isolated to a few special locations on the cathode. We cannot yet say what special conditions are required for its production.

[a]Opti-Fluor was obtained from Packard Instrument Company, 2200 Warrenville Road, Downers Grove, Illinois 60515. This fluid shows no chemiluminescence after 20 min when mixed 10 to 1 with 0.2 *N* LiOD.

CONCLUSION

Tritium was produced in 11 cells at levels between 1.5 and 80 times the starting concentration. Over 1500 tritium measurements were made on 53 cells of various designs. As can be seen in Table VIII, the total uncertainty in tritium content for these measurements is ±14 dis/min·ml, which is 0.1 times the starting concentration. Thus, the proposed tritium excess is well outside the uncertainty in the total measurement.

Fourteen inactive cells are described in this work and are used as reference standards. In addition, a cell containing normal water (0.2 *N* LiOH) has been studied recently and shows no tritium increase after 30 days. The effects of chemiluminescence, counting efficiency, and sampling error have been studied but are not described in this technical note. Based on this background, we believe that the tritium is real; it is not caused by contamination, and it is not a product of normal electrolysis.

The distribution ratio (gas/liquid) for tritium in the electrolyte is not a constant but appears to be influenced by the cell current density and, perhaps, by the cathode surface characteristics. This work produced values between 0.82 and 1.1.

Tritium production is found to occur after times as short as 2 days after electrolysis is started and with cathodes having an average D/Pd ratio as low as 0.70. Only ~1 cell in 10 is found to be active.

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TABLE VIII

Standard Deviation and Number of Data Points of Inactive Cells Compared to Excess Tritium* Values

Description of Data Set	Average Value (dis/min·ml)	Standard Deviation (dis/min·ml)	Number of Data Points
Background	19.3[a]	±2.4[a]	55
Closed cell	138	±14	446
Open cell, corrected for enrichment	120	±14	80
Open cell, uncorrected for enrichment	140	±31	96

*Excess tritium production: $70 - 1.1 \times 10^4$ dis/min·ml.
[a]Values in count/min·ml.

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A REVIEW OF THE INVESTIGATIONS OF THE FLEISCHMANN-PONS PHENOMENA

OVERVIEW

COLD FUSION

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A review of the recent investigations of the Fleischmann-Pons effect ("cold fusion") is given. A discussion of the proposed theories and models to account for the observations is also given. Suggestions for future research in this area are discussed.

INTRODUCTION

On March 23, 1989, Fleischmann and Pons[1] and Jones et al.[2] reported the observation of anomalous products during constant-current electrolysis of D_2O on palladium. Specifically, they reported production of excess heat, tritium, neutrons, and gamma rays.

Since that time, research has been performed throughout the world in an attempt to reproduce and confirm these claims. There has been widespread disappointment in that the phenomena cannot be switched on and confirmed in a simple way. Even those with electrochemical experience and plentiful resources (such as those at national laboratories) have reported negatively on the grounds that phenomena were visible only in sporadic bursts and "nothing consistent" could be measured. This sporadic nature of the effects, with periods of weeks in which observers do not record the phenomena reported by Fleischmann and Pons, remains a marked difficulty.[a]

TYPICAL CELLS

Most research into nuclear electrochemical phenomena uses cells in which the electrode pretreatment and solution types are varied. The cell described in Ref. 1, typical of the generally accepted cell design (Fig. 1), was a double-walled glass cell containing the electrochemical apparatus and monitoring equipment, e.g., temperature probes. The electrolytic solution was 0.1 *M* LiOD in D_2O. The electrodes were a cathode of palladium (1- to 6-mm diam) with an anode of platinum wire wrapped around it, separated by glass rods. In some designs, a catalyst for the recombination of the evolved gases (D_2 and O_2) was included either inside or outside the cell. Constant-current electrolysis was performed for periods of time varying from tens of hours to six months, with the current density ranging between 10 and 1000 mA/cm^2. The cell was calibrated by a joule heater supplying nonelectrochemical heat to the cell, the temperature difference ΔT between the inside of the cell and a water bath being measured (Fig. 2). The current was then turned on and the ΔT (and the corresponding power-out W_{out}) was compared with that expected for the heat on the grounds of thermochemical reasoning. If the cell was completely closed (recombination catalyst inside the cell), the power-in W_{in} can be calculated from EI, where E is the potential in volts and I is the total current in amperes. If the cell allowed the evolved gases to escape, or recombined them outside the cell, the power-in factor must be modified by subtracting the heat of recombination of D_2 and O_2 (the thermoneutral potential), equivalent to 1.54 V/mol^{-1}, from the potential factor.

The most common method of describing the results is in terms of "excess heat," which is given by[b]

$$\frac{W_{out} - W_{in}}{W_{in}} . \qquad (1)$$

[a]Conversely, there are already claims as to techniques that lead to an immediate switch-on.

[b]In the first year of examining the Fleischmann-Pons effect, there were many papers[4] that stressed alleged errors in calorimetry. However, for small cells, it is easy to measure (by means of thermistors) the temperature to ±0.01°C, and the changes in temperature above those expected are generally ~1°C. Particularly if stirring in the cell is good, it would seem difficult to have significant calorimetric errors.

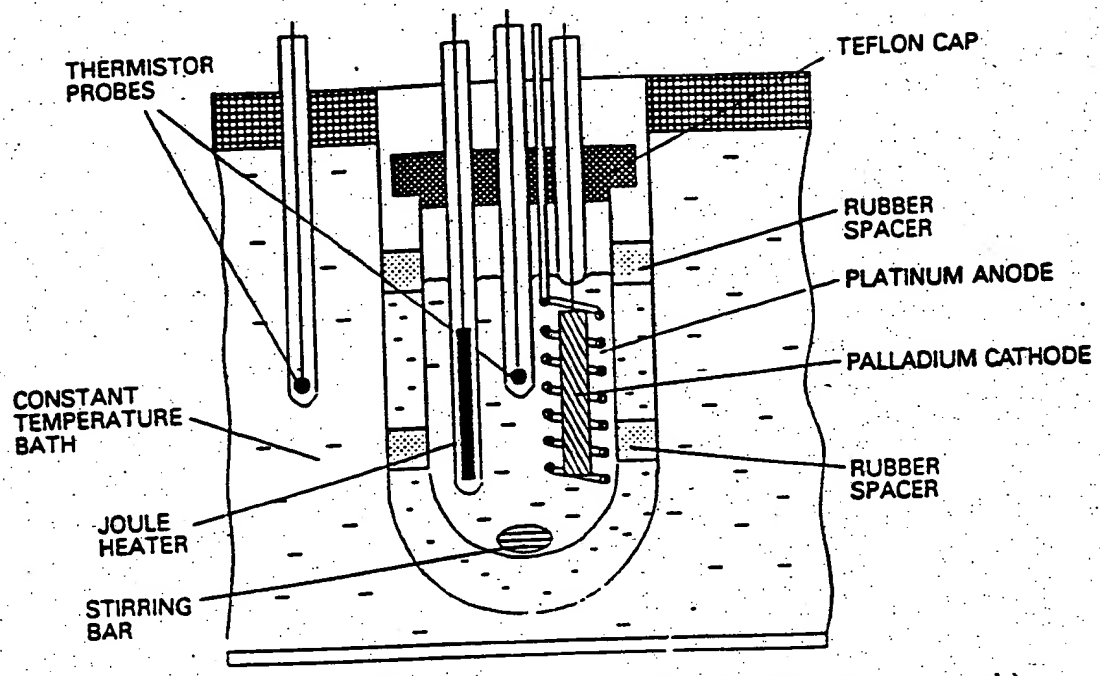


Fig. 1. Schematic of a typical Fleischmann-Pons–type calorimetric cell (not to scale).

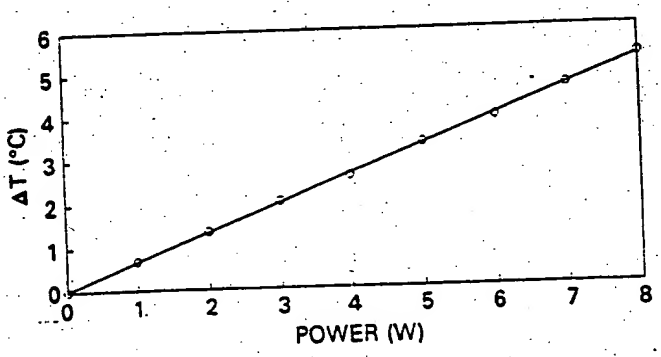


Fig. 2. Typical calibration curve for the cell shown in Fig. 1 (Ref. 3).

This also requires continuous monitoring of potential, current, and ΔT.

MEASUREMENT OF NUCLEAR PRODUCTS

The production of radiation from such cells can be divided into observations of (a) tritium, (b) neutrons, and (c) other types of radiation (including gamma and X rays). The paths leading to the formation of the first two types of radiation are shown below:

$$^2H + {}^2H \rightarrow {}^3H + {}^1H + 4.02\ MeV \qquad (2)$$

and

$$^2H + {}^2H \rightarrow {}^3He + {}^1n + 3.27\ MeV\ . \qquad (3)$$

The production of tritium from reaction (2) is easily characterized by the technique of liquid scintillation counting, in which a scintillating mixture is added to a sample and the resulting excitation analyzed. Several problems, however, exist with this technique. The chemiluminescence of the scintillation cocktail can be mistaken for high tritium activity. Thus, it is imperative that the analyzing instrument be capable of registering the luminescence effect. If any chemiluminescence is detected, the result should be thrown out until the level of chemiluminescence is zero (as will normally occur in a few hours).

A further complication is the buildup of tritium on normal electrochemical grounds. During electrolysis of a solution containing a mixture of the isotopes of hydrogen, a preferential evolution of the lightest isotope occurs—the so-called isotopic separation phenomenon.[5] Thus, a natural increase in tritium activity is expected. In an alkaline solution, the value of the separation factor is −2 on palladium (see Table I). As D_2O contains a trace amount of tritium, a natural increase to a value of approximately twice that of the original solution occurs (see Appendix). For example, if the tritium activity is originally 100 distintegrations per minute per millilitre (dpm/ml), after prolonged electrolysis including frequent additions of tritium-containing D_2O, the final value would be expected to be of the order of 200 dpm/ml (on classical grounds).[3]

If, however, the above sources of error are tak into account, tritium measurement remains the e nuclear particle phenomenon to quantify.

Neutron detection is much more comple

TABLE I

Values of $S_{H\text{-}T}$ and $S_{D\text{-}T}$ on Various Metals[6]

Metal	i (mA/cm^2)	$S_{H\text{-}T}$
Palladium	30	6.6
Palladium	100	6.6
Palladium	300	6.9
Platinum	16	7.6
Platinum	32	7.2
Platinum	100	8.8
Titanium	25	6.2
Titanium	75	6.1
Titanium	250	7.0
Iron (pH = 6.5)	20	9.1
Iron (pH = 7.5)	20	9.6
Metal	**i (mA/cm^2)**	**$S_{D\text{-}T}$**
Palladium	100	2.6
Palladium	300	1.9
Platinum	20	2.2
Platinum	32	2.6
Platinum	64	2.5
Platinum	80	3.0
Titanium	60	2.2
Titanium	90	2.5
Titanium	90	2.6
Titanium	260	2.6

more expensive. It requires a great deal of equipment and experimental experience. Cosmic-ray showers that lead to false neutron counts require elaborate methods to be detected and rejected. One of the most efficient neutron detectors is the NE-213 liquid scintillator detector. With suitable electronics, this detector has an overall efficiency of ~5%.

The production of other radiative particles (e.g., X rays, gamma rays, etc.) is secondary to the production of neutrons or tritium. Thus, their detection and quantification are not described here. Note, however, that the existence of such particles could provide valuable information regarding the mechanism of any nuclear reaction occurring under such experimental conditions.

ELECTROCHEMICAL EXCESS HEAT PRODUCTION

The production of excess heat can be categorized into two sets of observations: the so-called "low-level" heat, corresponding to an excess heat [as defined in Eq. (1)] <100%, and excess heat >100%. Most reports

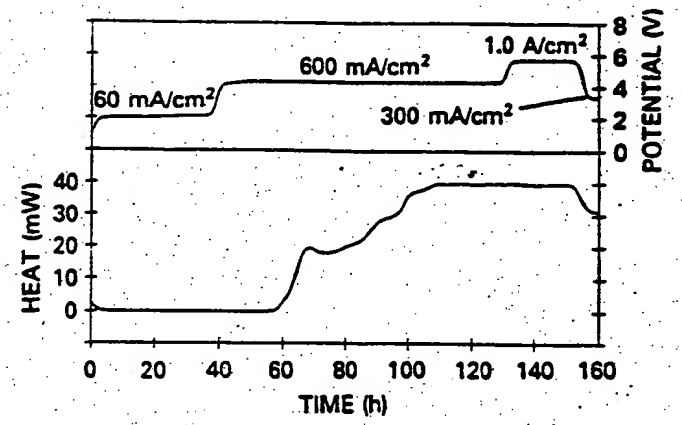


Fig. 3. Appleby and Srinivasan's Pd-D_2O experimental results.[8]

fall into the first category. The excess heat is rarely a constant phenomenon; rather, it occurs in bursts of activity, sometimes, but not always, associated with a change of system parameters (a change in current density, for example). Such heat bursts occur over a broad time span between minutes to days. In only a few cases has it been possible to correlate production of excess heat with production of radiation.[7]

The first reports by Fleischmann and Pons[1] gave a power output of 26 W/cm^3, corresponding to an excess heat of ~111%. Their recent claims are of a higher output of ~600%.

Srinivasan and Appleby[8] at Texas A&M University used an ultrasensitive microcalorimeter in which only very small (0.01-cm^3) electrodes can be analyzed. Using this instrument,[c] they claim the highest reproducibility rate at ~90% (Fig. 3). The levels of excess heat, however, are only of the order of 10%. Blank cells with H_2O produce negligibly low effects. Replacement of the lithium electrolyte (either ^{6}LiOD or ^{7}LiOD) by the sodium equivalent (NaOD) reduces excess heat production by ~85% if the replacement is performed when the experiment has been running for some time (Fig. 4). The effect of *starting* with a sodium electrolyte is not yet known.

Kainthla et al.[9] at Texas A&M have observed excess heat in 4 out of 28 cases (Fig. 5). They used a variety of cells. In some, gases were recombined outside the cell; in others, the cells were closed with a recombination catalyst inside the cell. In general, excess heat of ~10 to 30% was observed, occurring in bursts. In one cell, an excess heat burst was seen with an associated burst of tritium production. Claims of errors in the calorimetry are dealt with by the evidence that when a cell ceases to show excess heat, the heat output falls back exactly on the calibration line. Gas

[c]This calorimeter has stainless steel walls.

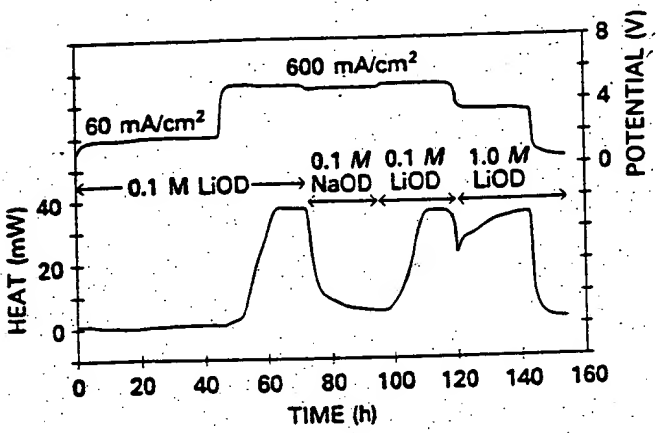


Fig. 4. The replacement of LiOD by NaOD in the Srinivasan and Appleby experiment,[8] showing almost complete reduction of excess heat.

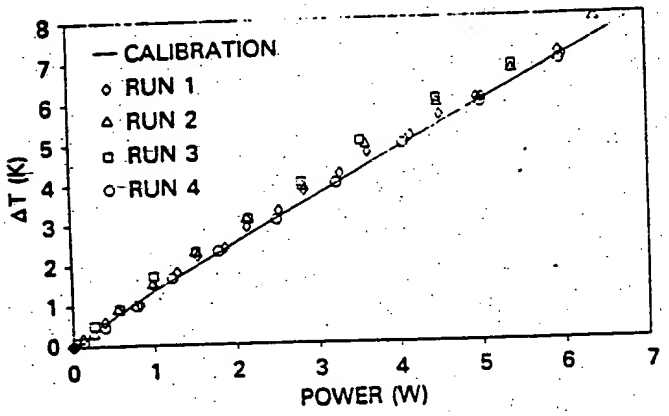


Fig. 5. An example of the excess heat measurement from Kainthla et al.[9]

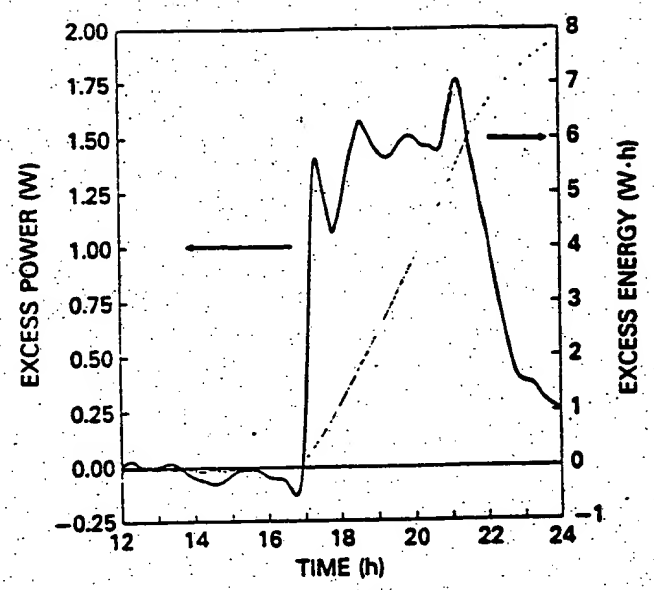


Fig. 6. Excess heat reported by McKubre.[10]

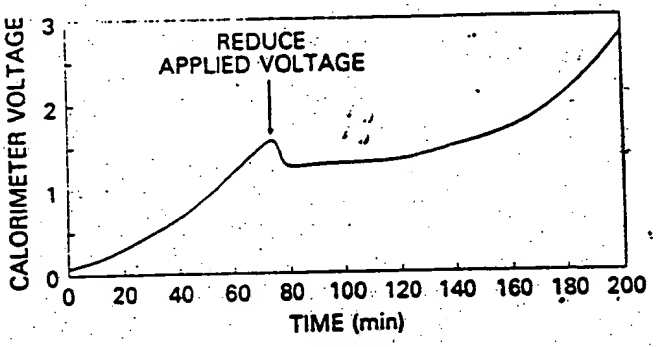


Fig. 7. Excess heat reported by Oriani et al.[11]

recombination as another possible error is discounted by the evidence that the faradaic efficiency is 100% (±2%). The absolute power generated in one of these cells corresponds to 9 W/cm^3.

McKubre[10] at SRI (formerly Stanford Research Institute) (Fig. 6) used a high-pressure D_2 electrochemical cell that reduces anode polarization. This cell was placed in a flow calorimeter that, by means of an electrical heater and electrochemical power, was maintained at a constant total power. Any process that gave heat in excess of this power was detected as an increase in the calorimeter outlet temperature. Results have shown 20 to 50% excess for periods of up to several days. In addition, there is tentative evidence of the production of ionizing radiation from within the palladium cathode.

In addition to calorimetric measurements, researchers at SRI also studied the resistance of the palladium electrode and its interfacial electrochemical impedance. These measurements provide fundamental information on the deuterium/palladium (D/Pd) ratio and the nature of the electrochemical kinetic processes occurring at the surface.

Oriani et al.[11] at the University of Minnesota observed 100 W/cm^3 in two cells in a heat flow calorimeter. The evolved gases were separated using a glass cylinder between the electrodes, perforated by many small holes to permit ionic conductivity in the cell. These cells were run in a potentiostatic rather than galvanostatic mode. As have many other workers, Oriani et al. observed frequent runs where no excess heat was produced, and the heat output fell exactly on the calibration line. This was also true for several experiments with H_2O. When the cells showed excess heat, they did so in a definite manner, and after a certain waiting period (16 and 22 h of constant input power in this case) (Fig. 7).

Huggins[12] at Stanford University originally observed 7 W/cm^3 of excess heat for 12 days in three out of five cells. This corresponds to 30 to 35% excess.

Recently, he observed 23 to 24 MJ/mol palladium from a closed cell.

Wadsworth et al.[13] at the University of Utah reported ~60 W/cm^3 excess in five cells on several occasions. Again, this excess occurred in bursts rather than as a constant phenomenon (Fig. 8).

Champion[14] in Tennessee originally claimed up to 600% excess heat using a radio-frequency (rf) heterodyne beat method. However, the actual amount of rf absorbed into the system was difficult to measure. An on-site visit by researchers at Texas A&M failed to confirm these high levels, but did witness ~60% excess.

Adzic et al.[15] at Case Western Reserve used a cell of the type found in Ref. 1, in a battery-run calorimeter. In two closed cells with palladium in LiOD, a small excess heat was observed over an extended time. With palladium in LiOH or platinum in LiOD, no similar excess was observed. In an open cell, with 4 mm of Johnson-Matthey palladium, a 20 to 45% excess was observed over an extended time. Lithium was found to penetrate 200 nm into the palladium bulk.

Schoessow and Wethington[16] claim up to 400% excess in one cell, and 60% in the other (only two cells have been fabricated).

Santhanam et al.[17] at the Tata Institute reported 0.2 MJ/cm^3 after a 48-h period from a titanium cathode using a current density varying from 33 to 66 mA/cm^2. Corresponding data for a palladium cathode showed no excess heat. Characteristic cracking of the electrode was observed using acoustic emission monitoring equipment.

Hutchinson et al.[18] at Oak Ridge National Laboratory have reported four out of four cells produced 3 W/cm^3, equivalent to an 18% excess. Their original claims were for the same levels for one cell out of two after 100 days of charging.

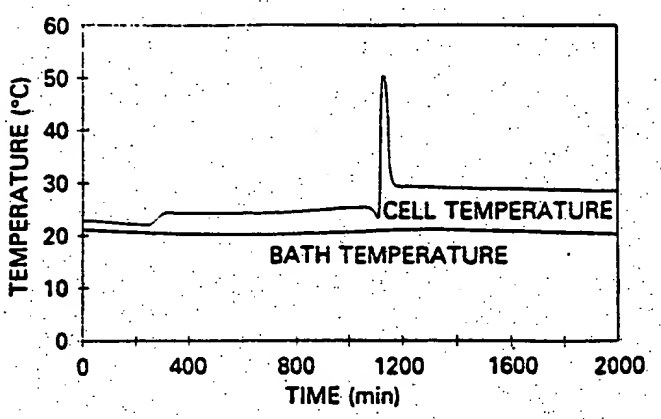


Fig. 8. Excess heat reported by Wadsworth et al.[13]

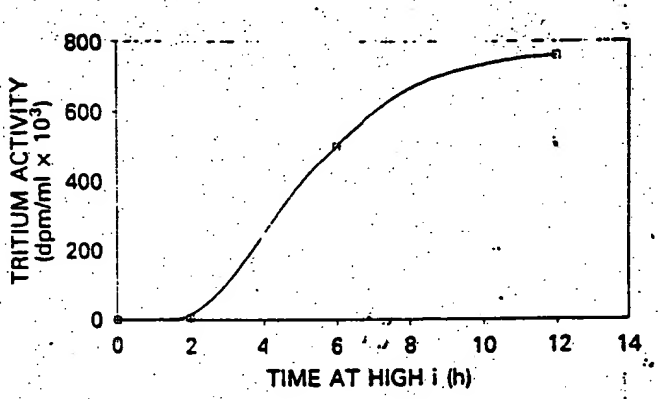


Fig. 9. Tritium production from cell A7 from Packham et al.[19]

ELECTROCHEMICAL TRITIUM PRODUCTION

In general, the reports of radiation production in Ref. 1 were later discovered to be less certain than at first claimed. However, Schoessow and Wethington[16] and Packham et al.[19] reported the observation of high levels of tritium production in their cells. The normal buildup of tritium from the frequent additions of heavy water (which includes traces of tritium as a contaminant) could not account for the levels of tritium measured in the cells. Packham et al.[19] reported tritium production of 10^2 to 10^4 times the background levels in 14 cells out of 28 (Table II and Fig. 9). Moreover, one particular batch of 1-mm palladium produced tritium in all eight cells. The actual rate of tritium production fell between 10^{10} to 10^{12} atom/s·cm^2. A thorough search for contamination gave negative results (Tables III and IV). This search included tests of each component of the electrochemical cell, including an analysis of the virgin anode and cathode material by Los Alamos National Laboratory[20] (LANL). Confirmation of the actual levels of tritium in solution was obtained from three national laboratories and one private institute (Table V). All analyses were performed in a blind fashion.

In one cell, the production of tritium has been correlated with the production of excess heat[7] (Fig. 10). However, the tritium produced could only account for 0.1% of this excess heat, which was at a level of up to 25%.

Wolf et al.[21] observed tritium production in one cell at the level of 10^5 dpm/ml (Fig. 11). The tritium in this case was produced in one 12-h burst. After the burst, the tritium was slowly and gradually sparged out, leading to the conclusion that at least part of it was in the form of deuterium-tritium (D-T). Several other cells seemed to show low-level tritium production, above that accountable by separation factor differences alone.

Schoessow and Wethington[16] reported that two cells had produced tritium at levels of 10^5 dpm/ml. They used cathodes in the form of palladium buttons with platinum anodes.

TABLE II

Cell Identification, Electrode Treatment, Solution Type and Tritium Activity of Electrolyte Samples[6]

Cell	Electrode Pretreatment	Solution	Corrected ^3H Activity (dpm/ml)
A1	No treatment	0.1 *M* LiOD	3.8×10^4
A2	No treatment	0.1 *M* LiOD + 0.1 m*M* NaCN	
	After 16 days at 50 mA/cm^2 then for 8 h at 500 mA/cm^2 (May 1, 1989)		168
	50 mA/cm^2 for 4 days (May 5, 1989)		134
	50 mA/cm^2 for 3 h, 110 mA/cm^2 for 2 h, 200 mA/cm^2 for 20 min (May 6, 1989)		1.1×10^4
	50 mA/cm^2 (May 7, 1989)		1.4×10^4
	(May 7–13, 1989)		1.1×10^4
	(May 13–June 6, 1989)		7.5×10^3
A3	Anneal	0.1 *M* LiOD	4.9×10^6
A4	Anneal	0.1 *M* LiOD + 0.1 m*M* NaCN	1.2×10^5
A5	Acid etch	0.1 *M* LiOD	3.7×10^6
A6	Acid etch	0.1 *M* LiOD + 0.1 m*M* NaCN	3.3×10^4
A7	Electrochemical	0.1 *M* LiOD	
	Before high current density		102
	After 2 h at 500 mA/cm^2		5223
	After 6 h at 500 mA/cm^2		5.0×10^5
	After 12 h at 500 mA/cm^2		7.6×10^5
A8	Electrochemical	0.1 *M* LiOD + 0.1 m*M* NaCN	
	After 16 days charging and 8 h high current density (May 1, 1989)		192
	Electrolyte levels after 6 weeks at 50 mA/cm^2		5.0×10^5
	Recombined gas levels after 2 weeks of external recombination at 50 mA/cm^2		5.0×10^7
B3 (3 mm)	Anneal	0.1 *M* LiOD	6.3×10^4
B5 (3 mm)	Acid etch	0.1 *M* LiOD	48
Cell 1 (6 mm)	No treatment	0.1 *M* LiOD	117
Cell 4	(See Fig. 10)		
M1	No treatment	0.1 *M* LiOD	3000

Storms and Talcott[22] at LANL fabricated a very large number of cells (>100). They used various poisons of hydrogen evolution in an attempt to drive deuterium into the palladium. To date, 2 cells out of 91 have given high levels of tritium, in addition to 9 cells that have shown levels above the separation factor concentration (Fig. 12). The two cells with high counts had at 9000 and 12 000 dpm/ml, respectively. The poisoning approach was also used by Packham et al.,[19] but the addition of 0.1 m*M* NaCN seemed to lower tritium production in all cases (see Table II). Poisoning with such compounds as CN^-, thiourea, and other sulfur compounds (Storms and Talcott bubbled H_2S through their solution) is an approach that should be further investigated.

Iyengar et al.[23] at the Bhabha Atomic Research Centre (BARC) have reported the most impressive set of data regarding radiative particles. They report a tritium level of up to 10^5 dpm/ml in six cells. In one case in particular, they used a multicathode array consisting of palladium-silver alloys, in a circular orientation around a central anode. The duration of tritium production varies from as short as 4 h to as long as 49 days. They have investigated the effect of various different electrode materials including the alloys.

Adzic et al.[15] reported the discovery of low levels (up to 40 times background) of tritium in five of their electrochemical cells. The cell with the 40 times increase also showed 20 to 45% excess heat. Three of the fabricated cells had nickel as the anode material.

TABLE III

Blank Experiments During Tritium Analysis[19]

Sample	Count/min·ml^{-1}	Background-Corrected Activity (dpm/ml)
D_2O analysis 1	65	48
D_2O analysis 2	70	63
D_2O analysis 3	67	54
D_2O analysis 4	60	33
D_2O analysis 5	50	3
D_2O analysis 6	71	66
D_2O analysis 7	75	78
D_2O analysis 8	62	39
0.1 *M* LiOD analysis 1	75	78
0.1 *M* LiOD analysis 2	70	63
0.1 *M* LiOD analysis 3	74	75
0.1 *M* LiOD analysis 4	65	48
0.1 *M* LiOD analysis 5	60	33
0.1 *M* LiOD analysis 6	66	51
0.1 *M* LiOD analysis 7	76	81
0.1 *M* LiOD analysis 8	70	63
Neutralized 0.1 *M* LiOD	73	72
Neutralized 0.1 *M* LiOD + 0.1 m*M* NaCN	76	81
Dissolved nickel in acid analysis 1	78	87
Dissolved nickel in acid analysis 2	80	93
Dissolved nickel in acid analysis 3	76	81
Scintillation cocktail	49	---

TABLE IV

Mean of Blank Experiments During Tritium Analysis[19]

Sample	Count/min·ml^{-1}	Background-Corrected Activity (dpm/ml)
—BIOSAFE II Cocktail	170 ± 13	---
H_2O analysis	161 ± 16	0
D_2O analysis	210 ± 16	100
0.1 *M* LiOD analysis	220 ± 20	125
0.1 *M* LiOH analysis	157 ± 12	0
Dissolved nickel in nitric acid	140 ± 20	0
Tygon tubing in NaOH	105 ± 20	0
Rubber stoppers in NaOH	150 ± 20	0
Recombination catalyst in NaOH	140 ± 15	0
Dissolved shavings from cutters	160 ± 11	0
Dissolved shavings from vacuum chamber	164 ± 17	0
Dissolved shavings from spotwelder	155 ± 10	0

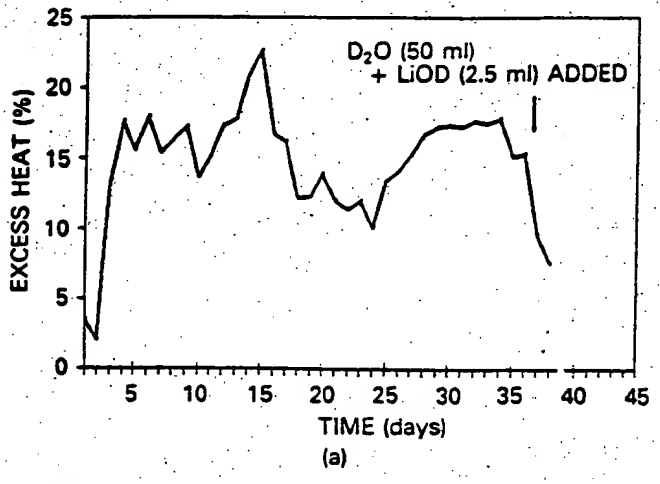
Malo et al.[24] at the Mexican Institute of Petroleum reported levels of 2200 dpm/ml in one cell out of three. Background tritium levels were at 85 dpm/ml. The time course of production resembles other findings in that only separation factor levels were found for up to 20 h. After 90 h, however, levels had risen to 2200 dpm/ml (Fig. 13).

Guruswamy[25] at the University of Utah recently reported finding ~100 times background levels in one cell and low-level production in other cells.

TABLE V

Confirmatory Results from Outside Sources on Various Samples[19]

	Sample 1	Sample 2	HTO Standard	0.1 *M* LiOD	D_2O
Texas A&M	2.13×10^6	1157	7.23×10^5	93	47
Battelle	1.96×10^6	1170	8.08×10^5	127	140
Argonne	1.96×10^6	1020	7.59×10^5	90	114
LANL	1.97×10^6	800 to 1300	6.50×10^5	113	161
General Motors	1.80×10^6	1000	Not analyzed		



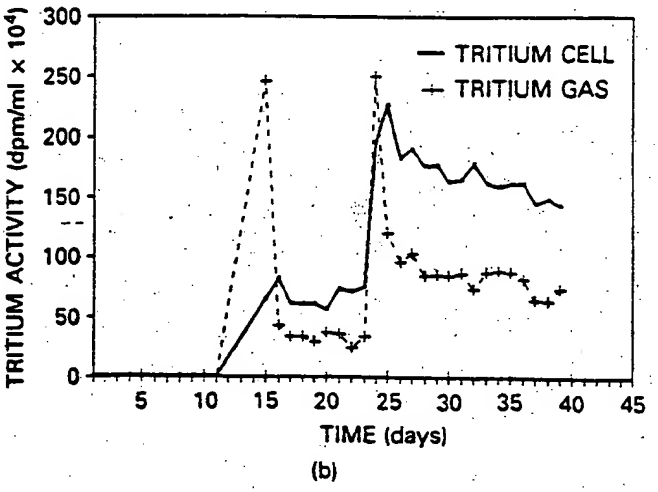


Fig. 10. The concurrent production of (a) excess heat and (b) tritium bursts from cell 4 from Kainthla et al.[7] The cell was at charging current from July 27, 1989. Time zero here is September 11, 1989.

Scott et al.[26] at Oak Ridge National Laboratory reported tritium activity of 25 times the background level in one cell with current densities varying between 200 and 600 mA/cm^2. This tritium occurred in a burst lasting 2 to 3 h. The typical sparging of tritium from the cell was also observed (Fig. 14).

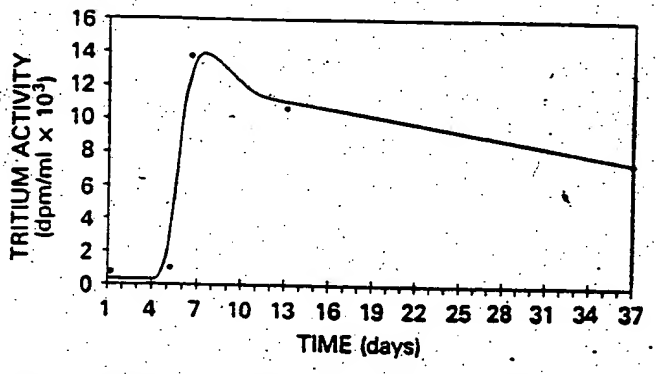


Fig. 11. Tritium production from cell A2 from Wolf et al.[21]

ELECTROCHEMICAL NEUTRON PRODUCTION

The great difficulty with neutron counting is lowering the background level sufficiently that a small effect can be seen if present. Also, the type of detector used can affect the validity of the results. A method to reject signals from cosmic-ray events must also be included in the experimental apparatus.

Jones et al.[2] at Brigham Young University used a BC505 neutron detector with a background rate of $\sim 10^{-3}$ n/s and an overall efficiency of 1%. The electrolyte used in this case was a complex mixture of inorganic salts in D_2O, at a pH of ~3. Neutron production was observed at rates up to five standard deviations above background in 11 out of 14 cases (Fig. 15). Jones et al. suggest that if the reaction occurs at the surface or if the conditions favoring fusion occur only intermittently (i.e., the time period for production is considerably less than the measuring time of the detection system), then the inferred fusion rate must be ~5 orders of magnitude larger than the detected $\sim 10^{-23}$ fusion/$(d\text{-}d)\cdot s^{-1}$.

Wolf et al.[27] observed the production of neutrons at 2.45 MeV in several bursts, at levels between three and five times the background levels. Out of 200 experiments performed, only 3 showed statistically significant neutron emission using the same piece of palladium wire using an NE-213 detector system (Fig. 16). Interestingly, it seems as if the nature of the surface was

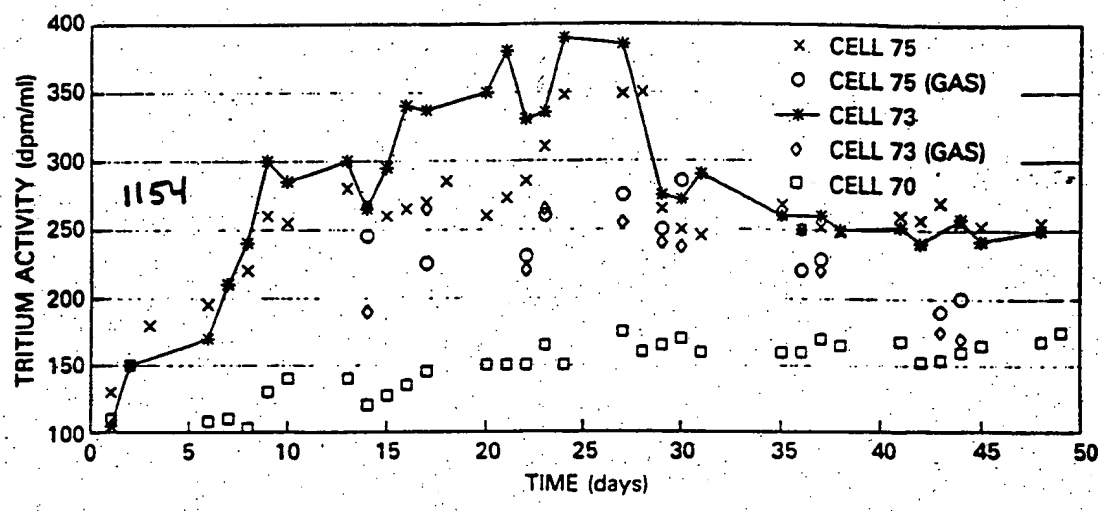


Fig. 12. Tritium production reported by Storms and Talcott.[22]

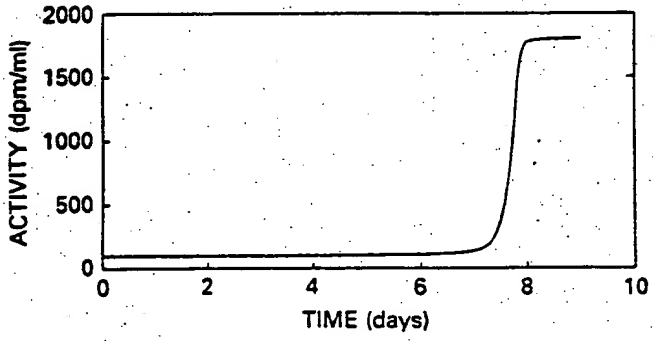


Fig. 13. Tritium production reported by Malo et al.[24]

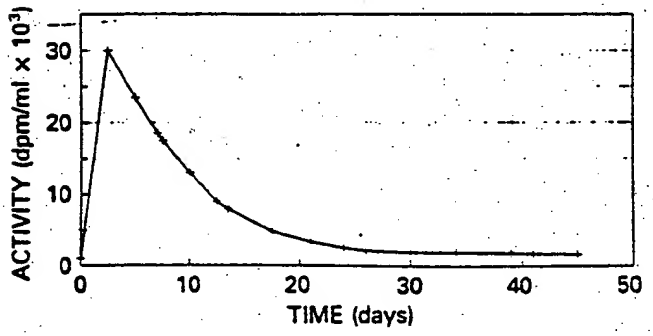


Fig. 14. Tritium production reported by Scott et al.[26]

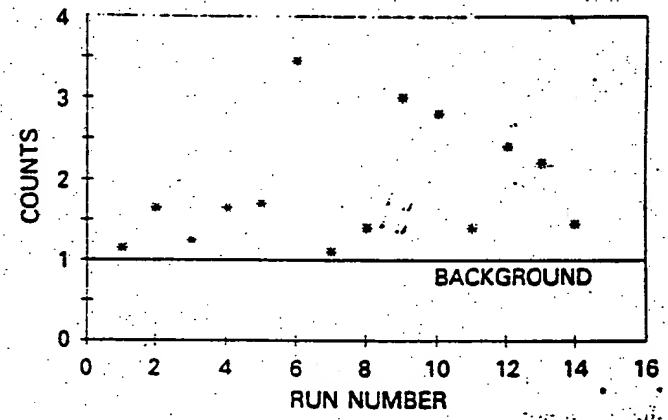


Fig. 15. Neutron production reported by Jones et al.[2]

directly related to neutron production: When a burst had died down to the background level, the electrode was taken out of solution, physically wiped, and replaced into the solution, and the effect reappeared.

The neutron production rate was ~1 n/s and was up to nine standard deviations above the background signal. The major achievement here was the lowering of the background count rate to <1 n/min. This allowed very low production rates to be measured. In addition, various tests showed that the signal was indeed coming from the cell, and not from a change in the background count rate (Fig. 17). Wolf et al.'s neutron detection system was calibrated using a Pu-Be source, a ^{252}Cf source, and a ^{252}Cf time-of-flight (TOF) measurement. This allowed a confidence in interpretation of the energy spectra produced in terms of knowing exactly where 2.45-MeV neutrons would appear. Both active and passive cosmic-ray shielding was in place throughout the course of the experiments, and pulse-shape discrimination was performed on the signal. A check was made to see if the detected events coincided with known cosmic-ray activity. This check proved to be negative.

The BARC results on neutrons[23] were obtained using counters of much lower efficiency than those

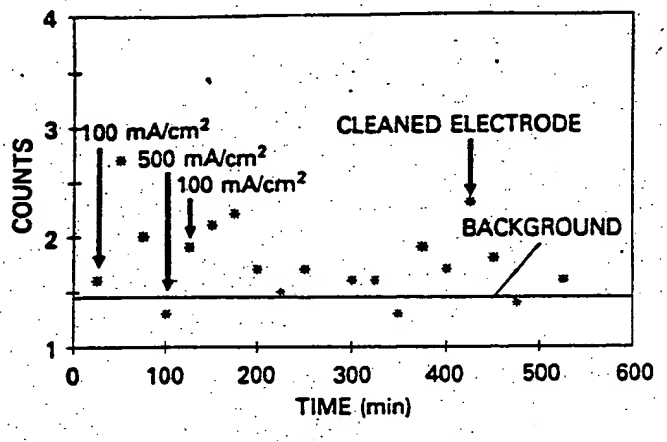


Fig. 16. Neutron production from cell A5 (first occurrence) reported by Wolf et al.[27]

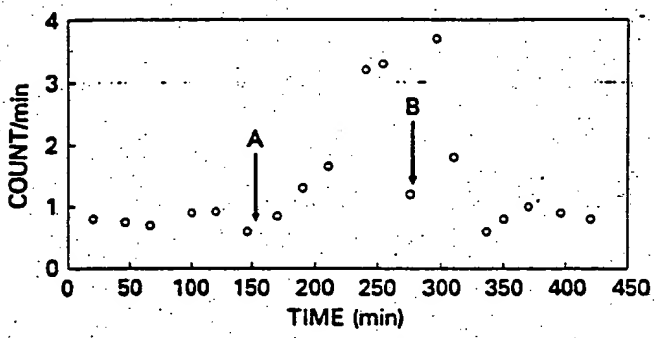


Fig. 17. Neutron production from cell A5 (second occurrence) reported by Wolf et al.[27] The cell was inserted in front of the counter at point A and rotated 5 cm away from the counter for the measurement at point B.

at Texas A&M, and with a background count rate of between 2 and 20 n/s (~1000 times higher than Wolf et al.'s experiments). In one of their experiments, a burst of neutron emission occurred for 40 h during an overall electrolysis time of 32 days. The rate of production was maximum at 1.3×10^3 n/s. At least four experiments gave neutron count rates 30 to 1000 times the high background rate (Fig. 18).

The Texas A&M and BARC groups could, therefore, estimate a branching ratio for production. It is significant that both groups measured a branching ratio of between 10^{-8} to 10^{-10}, although one of the BARC experiments did give a branching ratio of 10^{-2}.

OTHER RADIATION FROM ELECTROCHEMICAL EXPERIMENTS

Rolison and O'Grady at the Naval Research Laboratory[28] investigated the change in *m/z* ratios for species in the palladium electrode after electrolysis by time-of-flight secondary ion mass spectrometry (TOF-

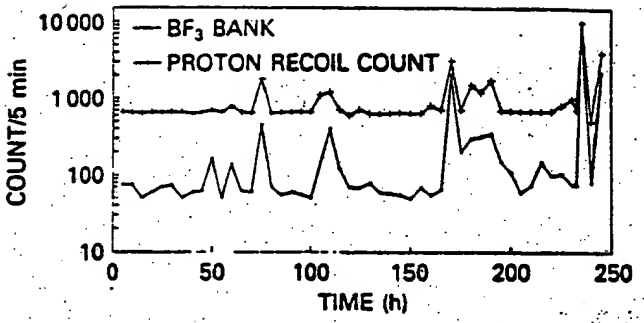


Fig. 18. Neutron production reported by Iyengar et al.[23]

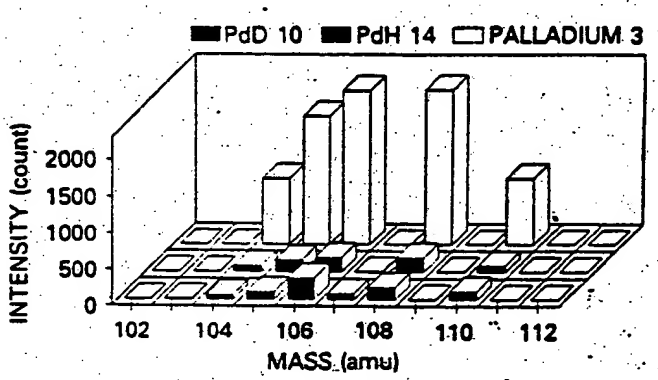


Fig. 19. The *m/z* ratio changes reported by Rolison and O'Grady.[28]

SIMS). They found an interesting near-surface enrichment of the *m/z* 106 species and a near-surface dimunition of the *m/z* 105 and 108 species.

In addition, the low-level impurities ruthenium, silver, and copper were found at significantly higher levels in the near-surface after long-term electrolysis than in the virgin material using X-ray photoelectron spectroscopy.

A blank experiment using palladium electrolyzed in H_2O showed no such enrichment. Mass spectroscopic analyses of the gases evolved when the electrical supply was stopped and showed constituents of *m/z*, 3, 4, 5, and 6 (Fig. 19). The assignments of these values were that they were due to dimers and trimers of the deuterium and hydrogen species, and not due to any tritium-containing species. Therefore, *m/z* 3 was H_3^+ and DH^+, *m/z* 4 was D_2^+ and H_2D^+, *m/z* 5 was D_2H^+, and *m/z* 6 was D_3^+. That is, there was no indication of $^3He^+$, T^+, $^4He^+$, TH^+, DT^+, TH_2^+, T_2^+, HDT^+, or Li^+.

Some of the normal reactions of palladium with 14-MeV neutrons are as follows:

$$^{104}Pd(n,p)^{104}Rh \quad (\sigma = 0.13 \text{ b}; t_{1/2} = 44 \text{ s}) , \qquad (4)$$

$$^{105}Pd(n,p)^{105}Rh \quad (\sigma = 0.70 \text{ b}; t_{1/2} = 36 \text{ h}) , \qquad (5)$$

$$^{110}Pd(n,\alpha)^{107}Rh \quad (\sigma = 0.014 \text{ b}; t_{1/2} = 4 \text{ min}) , \qquad (6)$$

$$^{110}Pd(n,2n)^{109}Pd \quad (\sigma = 2.0 \text{ b}; t_{1/2} = 13.6 \text{ h}) , \qquad (7)$$

and

$$^{108}\mathrm{Pd}(n,\alpha)^{105}\mathrm{Ru}\ (\sigma = 0.0022\ \mathrm{b};\ t_{1/2} = 4.5\ \mathrm{h})\ . \quad (8)$$

In addition, if the fast 14-MeV neutrons were thermalized by the interaction with the aqueous electrolyte, the following reactions could be seen:

$$^{102}\mathrm{Pd}(n,\gamma)^{103}\mathrm{Pd}\ (\sigma = 4.8\ \mathrm{b};\ t_{1/2} = 17\ \mathrm{days})\ , \quad (9)$$

$$^{108}\mathrm{Pd}(n,\gamma)^{109}\mathrm{Pd}\ (\sigma = 7.7\ \mathrm{b};\ t_{1/2} = 13.6\ \mathrm{h})\ , \quad (10)$$

and

$$^{110}\mathrm{Pd}(n,\gamma)^{111}\mathrm{Pd}\ (\sigma = 0.4\ \mathrm{b};\ t_{1/2} = 22\ \mathrm{min})\ . \quad (11)$$

Although the mass-to-charge data are intriguing, the authors state that it is difficult to explain by any known physical process. However, the spatial orientation of the enrichment suggests a surface mechanism for whatever process is occurring during their electrolysis. It is even more intriguing to note that it is the middleweight species that is enriched at the surface while the heavier and lighter isotopes migrate inward.

The accuracy of the SIMS work presented in Ref. 28 has been questioned, and it is currently being repeated.

An experiment by Taniguchi et al.[29] at the Osaka Prefectual Radiation Research Institute reported the detection of charged particles (3-MeV protons). The experiment was designed so that such particles could be measured, since they have a very short mean-free-path. One face of a palladium foil was used, the other side of the electrode being coupled to the radiation detector. There were a total of 30 electrolytic runs. In six of these, significantly higher count rates were observed. Again, the phenomena occurred in bursts. For 6 days, background levels were recorded. On the seventh day, the count rate began to increase and maximized at five times above background (Fig. 20). The time delays in similar runs were 1 day and several hours.

The energy spectra from these experiments show a high count rate of particles with a significantly lower energy than the expected 3.03 MeV [the Q value for the protons emitted in reaction (2)] (Fig. 21). This was explained by loss of proton energy due to the angle between the path of the particles and the detector. However, it would have been a simple matter to have calibrated the energy spectrum using a 3.03-MeV proton source to see the energy distribution in the detector. Taniguchi et al. have not ruled out other reactions contributing to the phenomena.

GAS-PHASE EXPERIMENTS

In addition to electrochemically loaded palladium and titanium samples, it is possible to load deuterium into such metals by the use of gas pressure. Such loaded materials have also been investigated for radiation production.

Such an experiment was performed by Wada and Nishizawa,[30] who passed an ac (60-Hz) 12-kV supply between two palladium electrodes in copper electrode stems in an atmosphere of D_2 gas, in a 1-Pa vacuum.

Neutrons were counted using a BF_3 detector, which had been calibrated with ^{241}Am-Be and ^{252}Cf sources. Two bursts of neutrons were seen after stimulation with the high-voltage source (Fig. 22a). Both bursts corresponded to 14 n/s (up to 2×10^4 times higher than background levels). Interestingly, the pressure of D_2 in the reaction vessel dropped during absorption of D_2 during the charging phase and increased after the first stimulating voltage (corresponding to D_2 being evolved from the palladium), but remained constant after the second stimulating voltage (Fig. 22b). This leads to the conclusion that the deuterium left in the palladium after the first stimulation is held more strongly than the situation before the first stimulation. After the experiment, the residual gases in the chamber were analyzed by mass spectrometry. Substantial amounts of species with mass numbers 1 through 6 were observed.

The results are explained by Wada and Nishizawa as being due to a supersaturated state of deuterium within the palladium. When the rod discards the excess

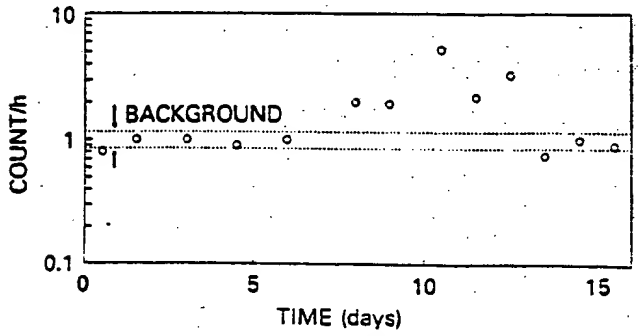


Fig. 20. The production of 3-MeV protons reported by Taniguchi et al.[29]

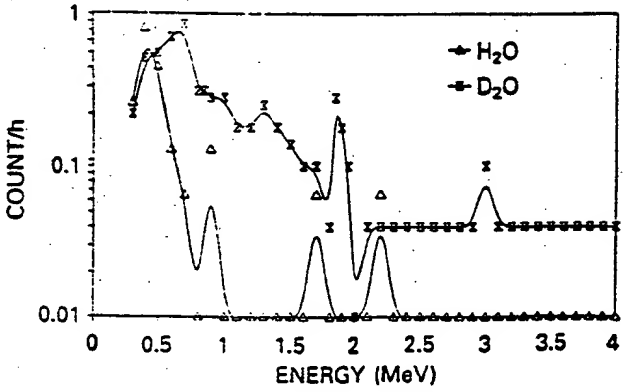
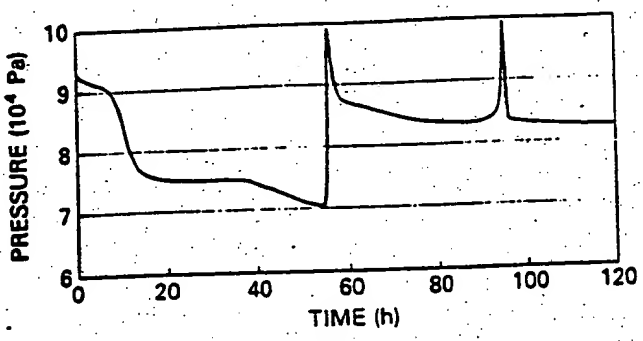


Fig. 21. The energy distribution of 3-MeV protons from Taniguchi et al.[29]



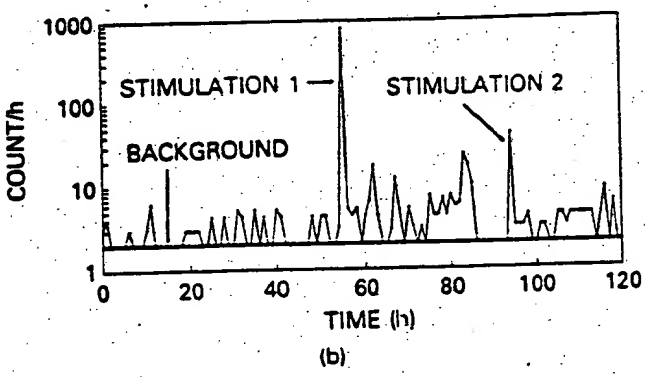


Fig. 22. (a) The gas-phase production of neutrons reported by Wada and Nishizawa[30] and (b) the pressure profile of deuterium in the apparatus as a function of time.

deuterium (after the first stimulation), neutrons are emitted. However, no explanation of the mechanism for such neutron production is given.

The experiments run by Menlove et al.[31] at LANL were performed using both titanium and palladium rods, and the reports contain information on both gas and electrochemically loaded electrodes. Neutrons were detected using ^{3}He detectors. Two different types of neutron phenomena were observed in the gas-phase experiments: one very short ($\leq$100-μs) duration, giving 10 to 100 neutrons (Fig. 23), and random neutron counting. The count rates from this experiment were on the order of 0.1 n/s, similar to the Jones et al.[2] results. Energy analysis of the neutrons was not possible since the yields were too low.

In the electrolytic experiments, two results showed $\sim 3\sigma$ above background, but no definitive statement was made. A third cell gave neutron bursts that continued for several days and was compared to six dummy cells (D_2O cells without electrodes). The largest burst corresponded to a neutron source of 130 neutrons.

Researchers at BARC have also investigated the phenomena in a solid-gas experiment.[23] They used titanium and palladium-silver disks, wafers, and cones, and powdered palladium black. Tritium was found using scintillation counting and autoradiography as well

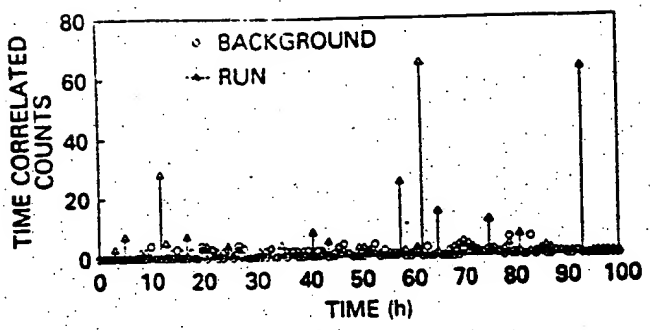


Fig. 23. The gas-phase production of neutrons reported by Menlove et al.[31]

as an X-ray technique. Levels of $>10^{10}$ to 10^{12} atoms of tritium were found.

CLUSTER IMPACT FUSION

An experiment by Beuhler et al.[32] at Brookhaven National Laboratory describes a fusion reaction produced by the impact of a cluster of D_2O molecules upon a TiD target. The protons produced from reaction (2) were detected. The accelerating energy of the cluster was varied. At 300-keV, the fusion rate was measured at -0.05 fusion/s. Blank experiments run with an accelerated H_2O cluster on TiD, or a D_2O cluster impacting on a target of TiH, showed no such behavior. The size of the cluster also seemed to be a criterion for fusion reactions occurring. Below a 20 D_2O molecule cluster, no fusion was observed. The peak maximized at -150 molecules and had a broad shoulder up to 1000 molecules (Fig. 24).

THE EXPLOSION PHENOMENON

It seems natural to imagine that explosions might occur in electrolytic cells that are producing a 2:1 mixture of D_2 and O_2. However, in many circumstances,

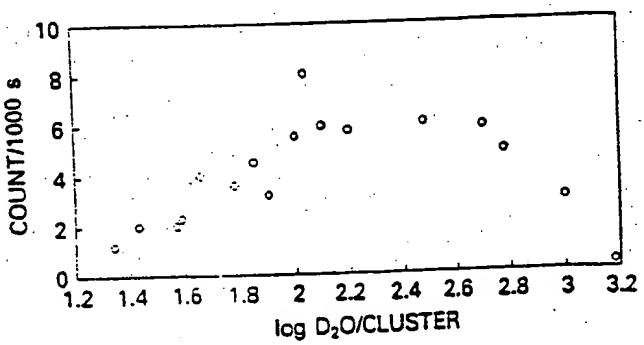


Fig. 24. The dependence of cluster size on neutron production during cluster impact reported by Beuhler et al.[32]

it does not seem possible that there is any initiating stimulus in the cell at the time of the explosion. For example, the electrodes are both normally covered by the electrolyte, and it seems unlikely that a spark generated in the solution between the two electrodes could ignite the dissolved gases. In general, the electrode materials are untouched by the explosion, and the glass cell (either the internal or external cell) is ruptured. In several instances, an electrode replaced in the cell after an explosion immediately explodes once again.[6] In other cases, cells that have been purposely switched off generate sufficient heat so that they are impossible to handle even 1 h later. This phenomenon seems to differ from the ignition phenomenon described in Ref. 1, but cannot be readily explained by a simple D_2/O_2 explosion.

THEORETICAL CONSIDERATIONS

Since Fleischmann and Pons[1] and Jones et al.[2] reported the cold fusion phenomena, which is difficult to explain by conventional nuclear physics, several attempts to interpret the excess heat as well as radiative particle emission have been made. Such explanations fall into two broad categories: a chemical reaction or nuclear fusion. The heat released by a chemical reaction corresponds to the range of a few electron volts per atom in contrast to the energy liberated in a nuclear reaction—on the order of millions of electron volts per nucleus. In an earlier paper,[33] eight possible chemical contributions to the excess heat seen in Ref. 1 were summarized. It was concluded that any chemical explanation would be improbable (see Table VI). No one chemical explanation suffices to explain the magnitude of the excess heat observed, and the large amount of tritium produced in the solution and gas phase[6,19] cannot be explained by *any* kind of chemical reaction. The second possible explanation is nuclear fusion. Different models to explain the cold fusion experiments have been suggested since they cannot be simply interpreted by existing nuclear physics.

There are two main characteristics of the cold fusion experiments. One is the large tritium-to-neutron ratio, on the order of 10^8, and the other is the burst-like nature and irreproducibility of the phenomena. A suitable cold fusion theory or model *must* explain both of these two features. The fusion models put forward can be divided into two parts. One is a hot fusion mechanism, which may be either caused by the development or collapse of cracks within the metal lattice, or triggered by cosmic rays. The second is a cold fusion mechanism that may also be divided into two sections: bulk and surface models.

Hot Plasma Explanation

Several workers have suggested that nuclear fusion occurs within some special areas of the palladium or titanium metal, where a hot plasma is formed. Mayer et al.[34] suggested that equal electric charges of opposite sign may be generated on each side of a crack as the crack spreads under the strong internal stresses caused by electrolysis (Fig. 25). As the crack grows, the charged surfaces separate while maintaining the constant electric charge, therefore increasing the voltage drop across the crack. A deuteron in the crack may be accelerated, under this large electric voltage drop, to an energy sufficient to overcome the mutual nuclear coulomb barrier. Gajda et al.[35] proposed that high-density and temperature pocket plasmas may be formed when defects or cracks in the metal electrode collapse. Hot nuclear fusion may occur in such plasma zones (Fig. 26). Seitz[36] suggested that the enthalpy of the formation of a D_2 molecule from the deuteron

TABLE VI

Summary of Chemical Contributions to the Fleischmann-Pons Effect

Chemical Explanation	W/cm
Partial exposure of electrode	0.20
Gas-phase recombination	0.30
Surface recombination	0.30
Alpha-beta phase transition	0.03
D/Pd ratio: chemical storage	0.30
Pd-D_2 dissociation: Pauling	0.90
Pd-Li alloy formation	0.08
Total	2.11[a]

[a]Compared to the 26 W/cm^3 reported by Fleischmann and Pons.[1] Excess heat in some cases is equivalent to more than 100 times the total heat of sublimation.

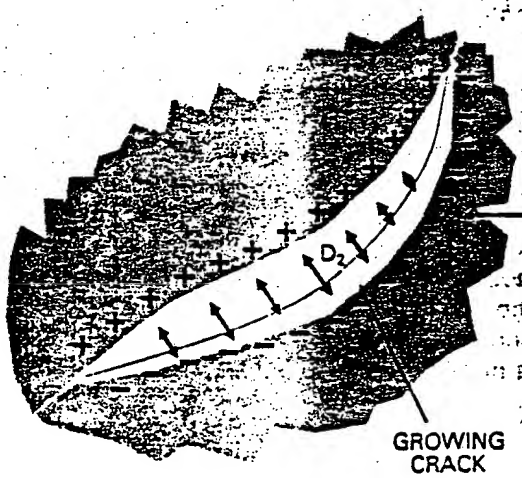


Fig. 25. The growing crack model proposed by Mayer et al.[34]

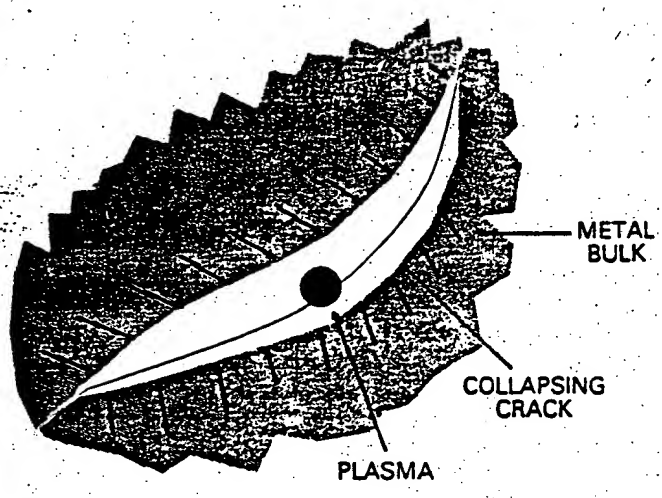


Fig. 26. The collapsing crack model proposed by Gajda et al.[35]

$$D^+ + D^+ + 2e \rightarrow D_2 + \boxed{20\ eV}$$

ENERGY OF FORMATION → SMALL HIGH-PRESSURE PLASMA BUBBLES

Fig. 27. The formation of plasma bubbles proposed by Seitz.[36]

within the solid state, which is ~20 eV, will produce small, hot, high-pressure plasma bubbles (Fig. 27). Nuclear fusion would occur in these locally very hot plasma zones. However, as Seitz points out, the surrounding cool metal would quickly quench the hot plasma.

Muon-Catalyzed Fusion

Muon-catalyzed nuclear fusion, triggered by cosmic rays, is another possible origin of cold fusion phenomena (Fig. 28). If a muon is trapped by a deuteron, the internuclear distance of the two deuterium nuclei would be reduced by a factor of ~200, relative to the spacing of normal deuterium nuclei. The muomolecular ion then has a very large cross section for nuclear fusion, a secondary muon being produced. Thus, one muon may catalyze a large number of fusion events, e.g., 200, before it is eventually absorbed by a metal atom. However, in palladium metal loaded with deuterium, placed in a muon beam, negative results were obtained,[37] which may indicate that the absorption of muons by the palladium lattice is too large to catalyze nuclear fusion.

Both hot plasma and muon-catalyzed fusion are grouped events. However, Shyam et al.[38] claim that such grouped events would appear with a probability of <20%, based on the statistical measurement of neutron production in cold fusion experiments. In addition, neither of these two models can account for the observed anomalous branching ratio.

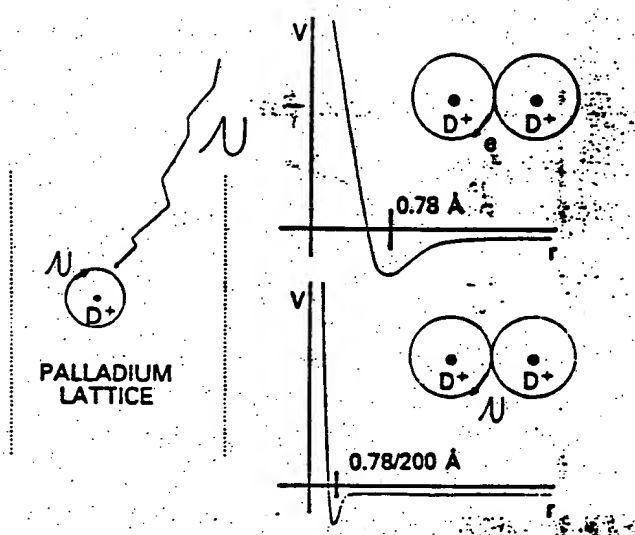


Fig. 28. The muon-catalyzed model proposed by Jones et al.[2]

Cold Fusion in Condensed Matter

A different theory is that the deuteron fusion rate is greatly enhanced in the condensed matter environment because of the combination of mutual Coulomb potential screening, the effective mass change, and resonance phenomena (Fig. 29).

In palladium or titanium metal, the coulomb barrier between two deuterons is greatly suppressed by the mobile electrons in the solid-state environment. Crowley[39] surmised that the absorbed deuterium in the metal was compressed to a high density to form a dense plasma of liquid metallic deuterium and hence developed a strongly coupled plasma model to account for the electron screen. Leggett and Baym[40,41] considered a many-body screening effect in the solid-state environment and discovered an unusual enhancement of the nuclear fusion rate. However, the calculated fusion rates were still too low to explain the experimental observations. Horowitz[42] and Burrows[43] modeled the metallic deuteride as a degenerate fermi gas of electrons and calculated the screening Coulomb potential. The calculated effective Gamov penetration factor was increased substantially in the metal environment. They claimed that the (p-d) reaction rate would be larger than or comparable to the (d-d) fusion rate in their model, and the distance between two deuterons would have to reduce to <0.1 Å in order to match the experimental results. However, *ab initio* calculations based on density function[44] and a pseudopotential total energy approach[45] showed that the distance between two deuterons in the palladium structure is on the

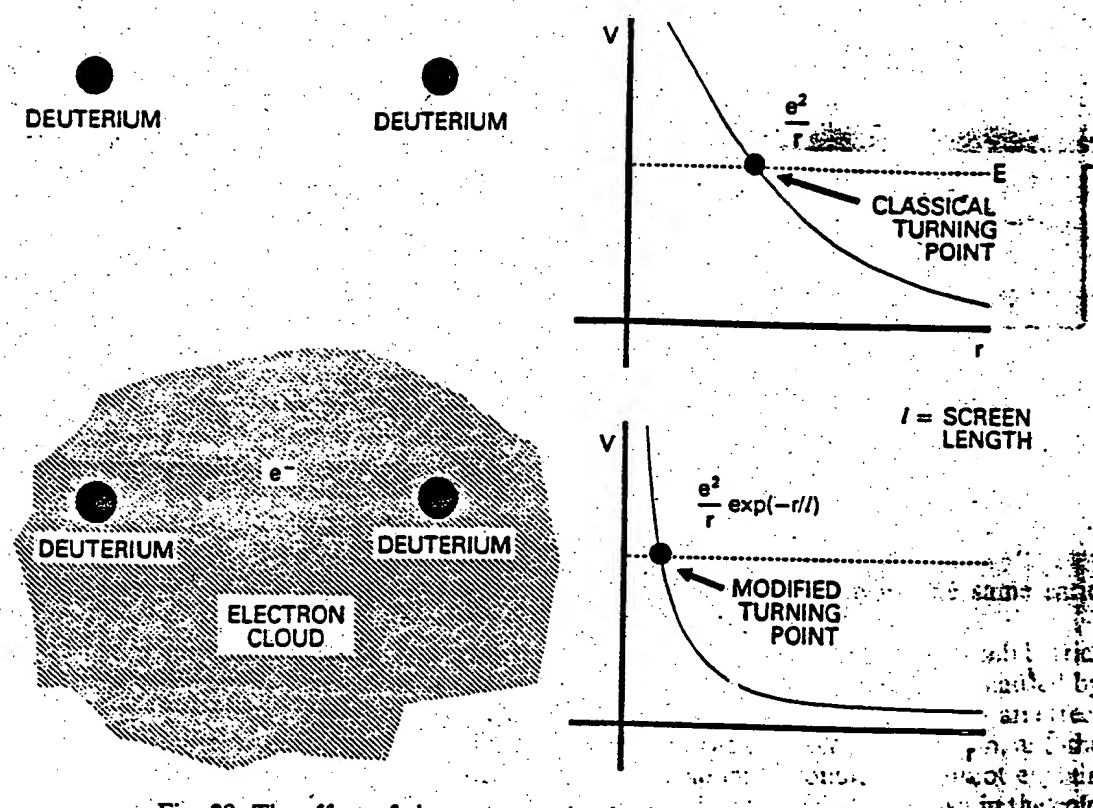


Fig. 29. The effect of electron screening in the palladium lattice.

order of 1 Å. Benesh and Vary[46] considered that the deuterons in the metal were confined to the bottom of a potential well with electrostatic screening of electrons present in the metal and hence calculated the penetration factor. The results showed that the calculated fusion rate was not sufficient to match the experimental value.

Vaidya and Mayya[47] modeled the deuterons as a mobile species in the palladium under electrolytic conditions (Fig. 30). A combined screen of Coulomb potential by itinerant deuterons and conduction electrons was considered. Ghosh et al.[48] proposed that delocalized deuterons in a uniform negative charge distribution of electrons formed a quantum plasma of bosons,

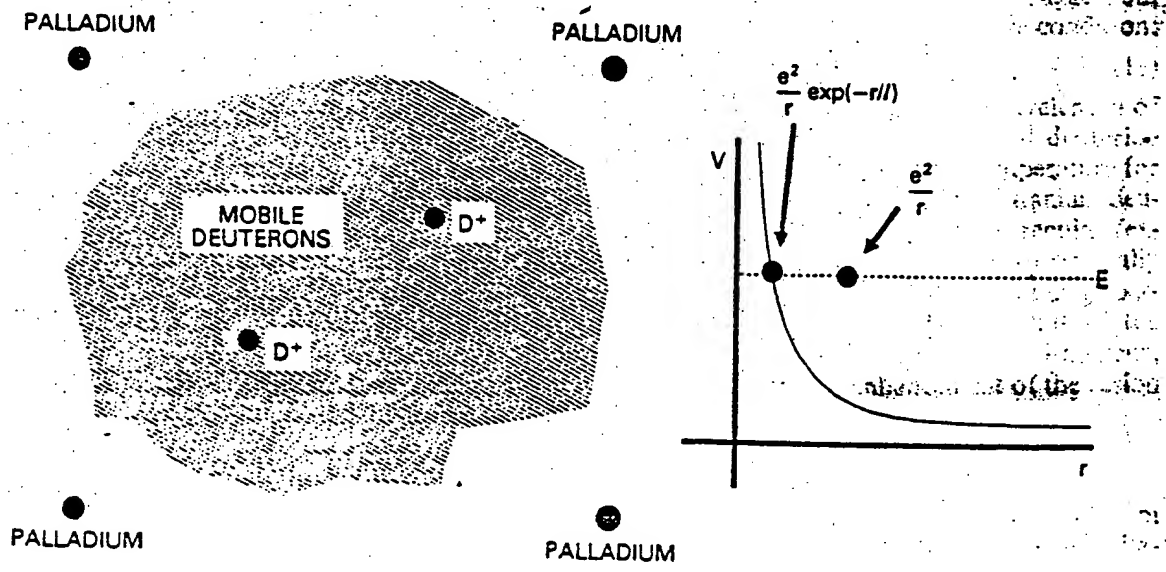


Fig. 30. The effect of mobile deuterons in the palladium lattice.

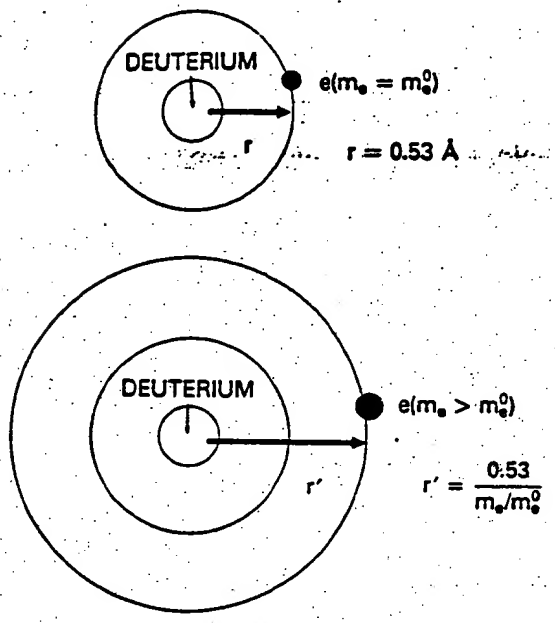


Fig. 31. Electron effective mass increase.

and such collective phenomena leads to a drastic enhancement of the nuclear fusion rate. The fusion rates calculated by Vaidya and Ghosh compare well with experimental values. However, the assumption that all the deuterons in the metal are fully mobile or delocalized may be questionable.

The effective mass change of an electron or deuteron in a heavily deuterated metal compresses the Coulomb potential barrier and enhances the fusion rate (Fig. 31). Jones et al.[2] proposed that high-effective-mass quasi-electrons formed in the deuterated metal lattice compresses the separation of deuterons and therefore enhances the quantum penetration factor. Tajima et al.[49] suggested that the deuterium electron and the conducting electrons of the metal form a screening electron cloud with an effective mass greater than the rest mass of the electron. They also calculated the decrease of the Coulomb barrier height by a dielectric medium constructed of core electrons and nuclei of metal atoms. Rabinowitz and Worledge[50] hypothesized that deuterons in the metal lattice move in a periodic potential well (Fig. 32). These deuterons behave as if they have a reduced effective mass. The tunneling probability of deuterons is then drastically increased. The electron screening of the Coulomb potential barrier was also considered in their model.

A deuteron moving in the metal lattice may find a local potential minimum and be confined in this quasi-stationary structure. Goldanskii and Dalidchik[51] suggested that, under the right conditions, resonance transparency may occur, which would greatly increase the effective collision frequency to a factor of 10^9 greater than that of the normal frequency, and hence

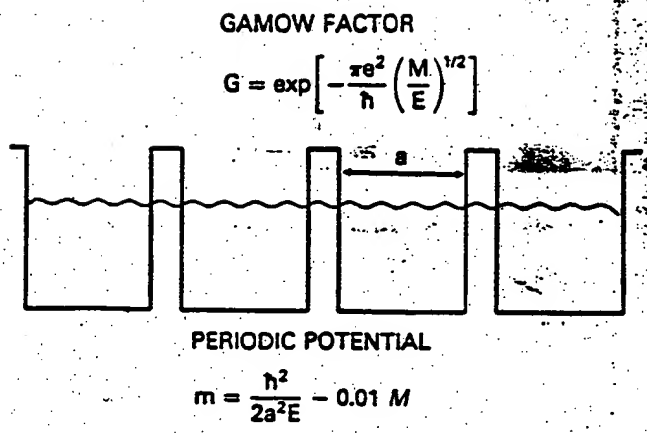


Fig. 32. Deuteron mass decrease.

enhance the nuclear fusion rate by the same ratio (Fig. 33).

However, the enhancement of the Coulomb barrier penetration factor in a metal environment, caused by screening effects of electrons and deuterons, an effective mass change of the electron and deuteron, and the occurrence of a resonance condition, cannot explain the sporadicity and irreproducibility shown in the cold fusion experiments.

Modeling the Quantum Barrier

Turner[52] hypothesized that transmission resonance on the atomic scale enhanced coulomb barrier tunneling. When the resonance condition

$$\int k(x)\,dx = \left(n + \frac{1}{2}\right)\pi \qquad (12)$$

is satisfied by the wave number of the particle crossing the potential well between two barriers, the transmission coefficient is 1. Based on Turner's suggestion, Bush[53] proposed a transmission resonance condition:

$$(2n + 1)\lambda/4 = L\ , \qquad (13)$$

with $n = 0, 1, 2, \ldots$ for the de Broglie wavelength of the particle within the lattice of a metal deuteride (Fig. 34). He calculated the resonance temperature for deuterons in the palladium deuteride and titanium deuteride lattices. Danos[54] considered both regular (exponentially decreased) and irregular (exponentially increased) solutions to the calculation of Coulomb barrier penetration. To obtain the ground state of the product nucleus, a third particle, the metal nucleus, was required. A substantial enhancement of the fusion rate was obtained.

Neutron Capture by Palladium

Jackson[55] suggested a chain reaction mechanism involving the radiative capture of neutrons by palladium nuclei (Fig. 35). A neutron is captured by a palladium nucleus to produce a different isotope of

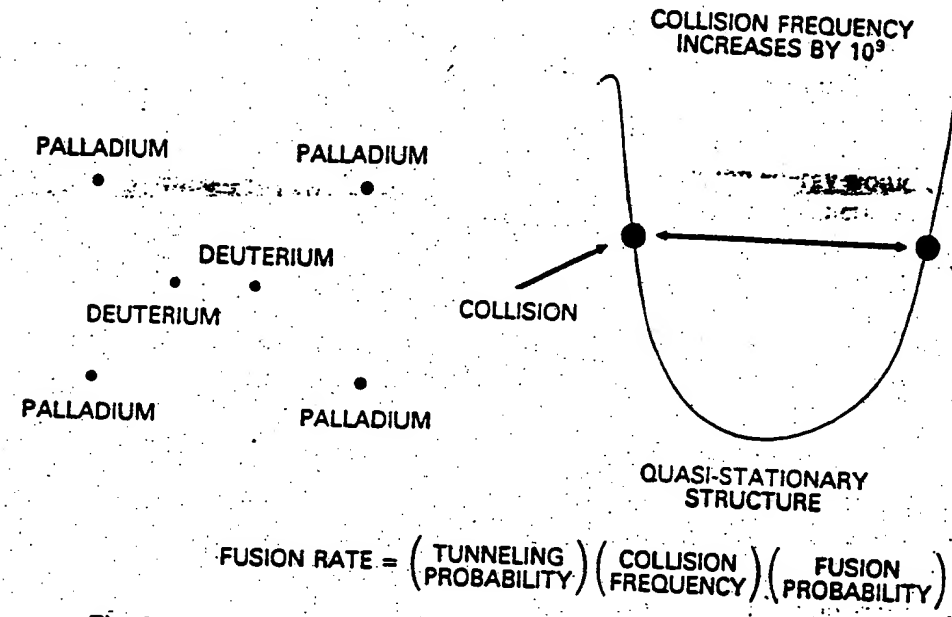


Fig. 33. The quasi-stationary state model proposed by Goldanskii and Dalidchik.[51]

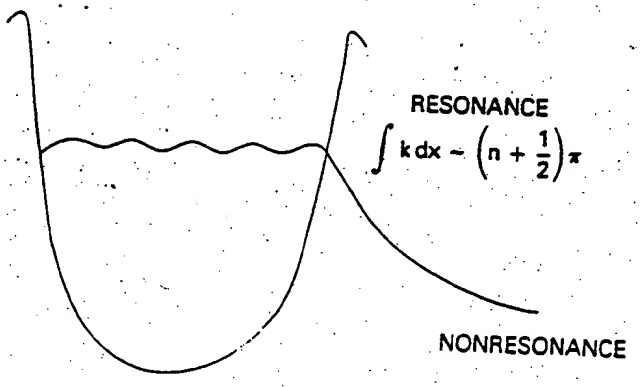


Fig. 34. Resonance tunneling as proposed by Bush.[53]

$$n + {}^{104}Pd \rightarrow {}^{105}Pd + \gamma$$
$$\gamma + D \rightarrow p + n$$

Fig. 35. The chain reaction model involving gamma-ray propagation.

$$n + {}^{104}Pd \rightarrow {}^{105}Pd$$
$$n + {}^{105}Pd \rightarrow {}^{106}Pd$$
$$n + {}^{106}Pd \rightarrow {}^{107}Pd({}^{107}Ag + e)$$
$$n + {}^{108}Pd \rightarrow {}^{109}Pd({}^{109}Ag + e)$$
$$n + {}^{110}Pd \rightarrow {}^{111}Cd + 2e$$

Fig. 36. The radiative capture model proposed by Budelov.[56]

palladium and a gamma photon, which causes photodisintegration of the deuteron and liberates another neutron. The chain reaction would be propagated in this way. The initiation of the chain reaction may be the enhanced deuteron density within the palladium lattice. Budelov[56] suggested that nuclear fusion released a neutron within the palladium lattice that would be absorbed by different natural isotopes of palladium (Fig. 36). The by-products would be heat and electrons. Rolison and O'Grady[28] observed the near-surface enrichment of ^{106}Pd and the near-surface diminution of ^{105}Pd and ^{108}Pd after electrochemical loading with deuterium in a palladium electrode. Jackson and Budelov's theory may explain the low neutron production rate compared to the high excess heat output. It would seem that radiative capture of neutrons by the metal nuclei may play a part in the cold fusion phenomena.

Quantum Electrodynamic

Jandel[57] suggested that nuclear fusion occurs in a hypothetical, strongly coupled, confining phase of the quantum electrodynamic domain (CQED), where an electric charge is confined, in analogy to color confinement in quantum chromodynamics. Electrons in the metastable CQED regime are always bound to either a positron forming an electromeson or an atomic nucleus forming an electronucleus. Deuterons may diffuse into the CQED regime, where fusion occurs with a very high rate, possibly attaining the order of 10^{11} fusion/s. The released fusion energy would then be used to expand and stabilize the CQED domain, which would grow spontaneously in a deuterium-rich environment (Fig. 37). The main product of such a nuclear

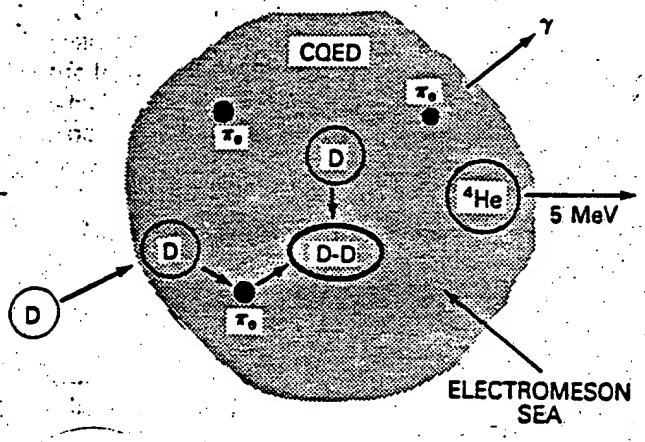


Fig. 37. The CQED model.[57]

reaction would be ^{4}He, which would diffuse out of the CQED domain, with a kinetic energy of ~5 MeV. The initiation of CQED domains may come from the large transient electromagnetic fields created, for example, by spontaneous fission of unstable transuranic nucleus, which exist in the palladium electrode as impurities. This model can explain the low neutron production compared to the excess heat, as well as the sporadicity of the experiment. However, this model predicts that the tritium output would be less than the neutron production, which is not consistent with experimental observations.

Superradiance

Bressani et al.[58] have discussed the cold fusion phenomenon based on a superradiant coherent interaction between matter and the electromagnetic field. The released fusion energy would be rapidly cooled by the quantized electromagnetic wave, which would explain the larger amount of excess heat compared to nuclear products.

Surface Model

All the models described above assume that fusion occurs *within* the electrode. However, the experimental observations seem to suggest that the *surface* of the electrode might be the site of such reactions. Specifically, it is suggested[6] that fusion reactions occur at specific points, or protuberances, on the surface of the electrode. Rolison and O'Grady's experimental observations of palladium isotope ratio shifts[28] suggest that the reaction is indeed surface, or near-surface, in nature. Jiang et al.[59] showed that the fusion reactions occurred only on minute areas of the electrode surface. Lin et al.[6,60] suggested a surface model, where dendrites grow during prolonged electrolysis on the electrode surface. The main components of the dendrites are impurities, such as nickel and copper, as well as the platinum anode material. Such a hypothesis is consistent with the sporadicity observed in the experiments.

It is well known that a very high electric field exists at the tip of a growing dendrite during electrolysis. When a deuterium gas layer grows on the tip of such

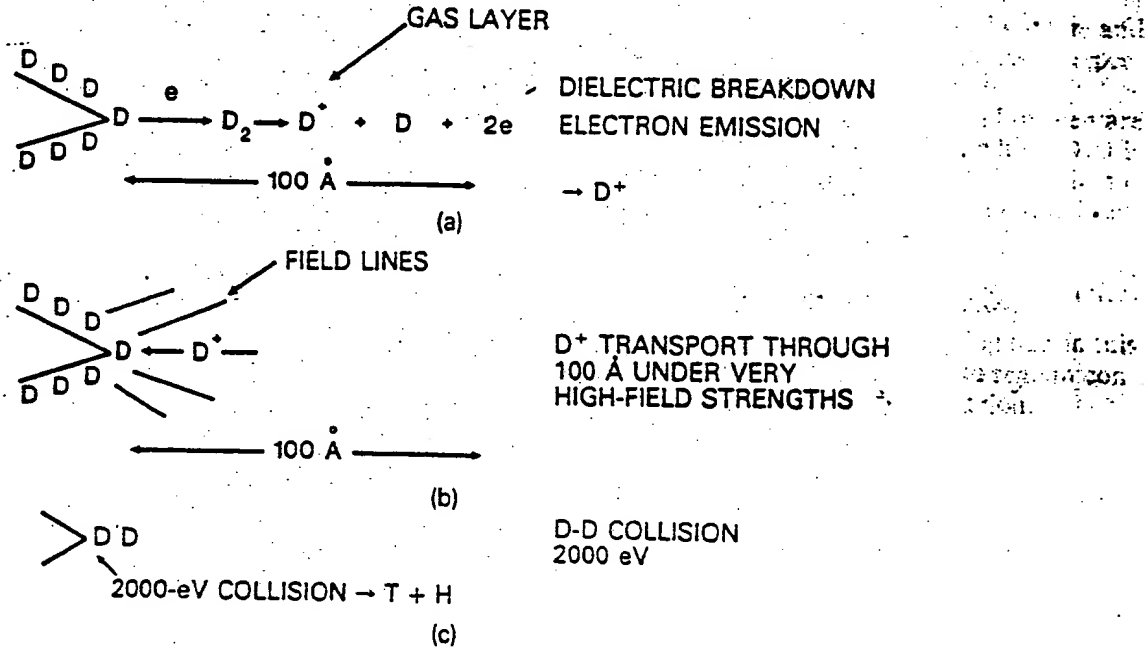


Fig. 38. The dendrite enhanced tunneling model proposed by Lin et al.,[60] accounting for all the observed phenomena.

a dendrite, an electron, emitted from the tip of the dendrite under the influence of the extremely high electric field, ionizes the deuterium to form a deuteron ion, which is accelerated to a high energy toward the electrode. The high-energy deuteron then collides with another deuteron adsorbed on the tip of dendrite, the resulting collision overcoming the Coulomb potential barrier for quantum tunneling (Fig. 38). Calculated fusion rates compare quantitatively with the experimental results. It is also suggested that the neutron-tunneling transfer reaction $d + d \rightarrow t + p$, similar to the Philips-Oppenheimer stripping phenomenon,[61] may occur with a greater probability, compared to the proton tunneling transfer reaction, in the dendrite surface condition. This model can effectively explain both the sporadicity and irreproducibility of the cold fusion experiments because of the characteristics of the growing dendrite, and also the large tritium-to-neutron ratio.

To summarize, a large number of models have been suggested to explain the experimental observations of the Fleischmann-Pons phenomena. The main characteristics of such phenomena are the large branching ratios of tritium-to-neutrons, $\sim 10^8$, and the sporadicity of the fusion experiments. Of the models discussed, only two, the QCED model suggested by Jandel[57] and the surface model proposed by Lin et al.,[59] can account for the sporadicity of the effect. However, as mentioned above, the CQED model would predict a *reverse* tritium/neutron ratio, which contradicts the experimental results.

Hence, at present, the only model that can completely explain the experimental observations or sporadicity and irreproducibility is that proposed by Lin et al.[60]

APPENDIX

Two experimental arrangements have been used here. One involves a cell from which deuterium and oxygen were allowed to escape freely into the atmosphere. Fresh D_2O containing 200 dpm/ml of tritium was added at intervals of 12 to 24 h. The buildup of tritium in solution, with no fusion, can be obtained as follows.

Changes in the tritium concentration occur due to the addition of fresh D_2O containing tritium and removal by electrolysis. The rate of addition of fresh D_2O into the cell R, in order to keep the volume V constant, must be equal to the rate of electrolysis of D_2O; i.e., $R = i/2F$. Thus, the rate of electrolysis of tritium out of the cell must be equal to the amount replenished by fresh solution and is given by this rate $(i/2F)$ times the mole fraction of tritium in solution, or $[Rn_T(0)/n]$, where $n_T(0)/n$ is the mole fraction of tritium and n is the concentration of all hydrogen, deuterium, and tritium species in the solution. The rate of removal of tritium through electrolysis is equal to R_T.

Thus, the factors affecting the concentration of tritium in the electrolyte can be related by

$$V dn_T(t)/dt = Rn_T(0)/n - R_T \ . \qquad \text{(A.1)}$$

Let S be the isotopic separation factor of tritium to deuterium, defined as

$$S = (n_D/n_T)_g/(n_D/n_T)_s \ . \qquad \text{(A.2)}$$

Equation (A.2) can be rewritten as

$$S = (R_D/R_T)/[n_D/n_T(t)] \ , \qquad \text{(A.3)}$$

where

R_D = rate of production of deuterium atoms

n_D = concentration of deuterium in the solution.

Under experimental conditions, $R_D \sim R$ and $n_D \sim n$; then we have

$$R_T = Rn_T(t)/nS \ . \qquad \text{(A.4)}$$

Substitution of Eq. (A.4) into Eq. (A.1) and integration gives

$$n_T(t)/n_T(0) = S - (S-1)\exp(-t/\tau) \ , \qquad \text{(A.5)}$$

with the tritium buildup time constant τ equal to

$$\tau = SnV/R \ . \qquad \text{(A.6)}$$

Equation (A.5) shows that the maximum tritium concentration in the solution due to isotopic separation at infinitely long times is S times the tritium concentration in the original solution.

According to Ref. 5, $S = 1.7$ to 2.2 and is hence taken to be 2. Thus, the time constants for a charging cell with a 15-ml volume and a total current of 0.15 A and for a calorimetric cell with a 100-ml volume and total current of 0.5 A are 22.2 and 44.4 days, respectively.

In the other situation, deuterium and oxygen are recombined outside the cell and the resulting D_2O is reintroduced into the cell. In this case, as no tritium is lost due to the electrolysis and no fresh solution is added, Eq. (A.1) becomes

$$V dn_T(t)/dt = 0 \ , \qquad \text{(A.7)}$$

giving $n_T(t) = \text{constant} = n_T(0)$, showing that in this case the concentration of tritium should remain constant in the absence of any nuclear reaction.

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Cold Nuclear Fusion Induced by Controlled Out-Diffusion of Deuterons in Palladium

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A gigantic neutron burst of $(1-2)\times10^6$ n/s has been detected from deuterated Pd plates with heterostructures set in a vacuum chamber. An explosive release of D_2 gas, biaxial bending of all the samples, and excess heat evolution were also observed at the same time. It has been concluded that these phenomena are caused by the cooperative production of D accumulation layers at Pd surfaces due to controlled out-diffusion of D-atoms.

KEYWORDS: cold nuclear fusion, deuteron, deuterium gas, palladium, heterostructure, out-diffusion, neutron emission, biaxial strain, heat evolution, cooperative phenomena

Since Jones *et al.*[1] and Fleischmann and Pons[2] reported that nuclear fusion occurred at room temperature in Pd or Ti cathodes during the electrolysis of D_2O, much effort has been made to reinvestigate the possibility of the electrolytically induced cold fusion in condensed matter.[3-12] Spontaneous neutron emission due to the fusion of D-atoms has also been observed during the process of soaking Ti powder into D_2 gas up to 40 atm, followed by cooling with liquid nitrogen and heating.[13] More recently, it has been reported that D^+ ions accelerated to more than 1 keV caused fusion at a high rate in deuterated Ti[14] or Pd.[15] Although the "high-energy" nuclear fusion in solids can be well undertood within the current theory because the fusion rate at 1 keV has been calculated to be more than 10^{13} times larger than that at 300 eV or less,* the observed neutron emission without application of high voltages[15] has given evidence of cold nuclear fusion. In this letter, we report a new technique for inducing "low-energy" nuclear fusion at room temperature in solids. By making use of this technique, we have observed a gigantic neutron burst and, at the same time, an explosive release of D_2 gas from deuterated Pd (Pd:D) plates as well as a biaxial bending of the samples. We have also detected excess heat evolution.

The key process in the present study is the formation of D accumulation layers at solid surfaces by controlling the D-atom out-diffusive transport with hetrostructures. Namely, one of the surfaces of a Pd:D (α-phase) substrate is covered with a thick Au-film in order to prevent the leakage of D-atoms from this side. In the present experiment, the substrates were obtained by immersing annealed Pd plates (99.9%; thickness=1.0 mm) into D_2 gas (99.9%; 0.5 atm) for 24 hours. The other surface is covered with a thin film having a diffusion constant of D less than Pd. This layer appropriately controls the out-diffusion of D-atoms passing through this interface. In the present work, we used a film with a thickness of less than 100 Å containing mainly Mn and O, which we call Mn–O film in this letter. Thus, the D accumulation layer can be formed at the interface during the out-diffusion processes of D-atoms by decreasing the pressure of ambient D_2 gas. It will be shown later that the formation of the β-phase layer can provide cooperative feedback to cause further accumulation of D-atoms.

As soon as the sample preparation was completed, we set three of these samples in another stainless-steel chamber, as schematically shown in Fig. 1, and evacuated it. Neutrons were counted by using a BF_3 detector (Aloka Co., Ltd: TPS-451S) set at 38 cm from the samples. The leak detector (Varian Ltd: 925-40), monitoring gases of mass numbers less than 6, was also set in the vacuum chamber. About three hours after pumping, we observed the virtually simultanious occurrence of the following events: (1) neutron emission of 0.1–0.2 mSv/h

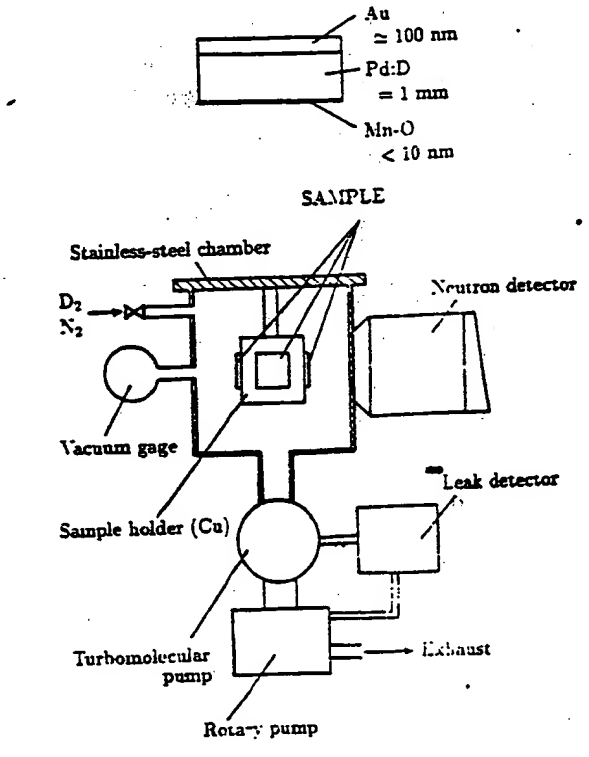


Fig. 1. Schematic diagram of the measurement apparatus.

*J. Rafelski, M. Gajda, D. Harley and S. E. Jones: private communication.

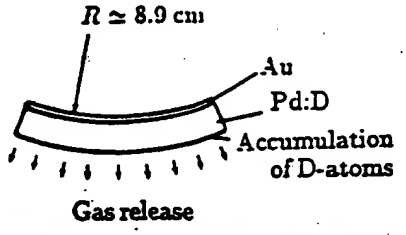
for 2–3 seconds, (2) explosive release of gas from the samples, and (3) biaxial bending of all the samples due to uniform expansion of the sufaces with a thin Mn–O film (see Fig. 2). When the samples were taken out from the chamber, we found an increase in the temperature of about 50°C on the stainless-steel sample holder as well as on all three samples. We also observed that the color of Au deposited on one of the surfaces was lost, which indicated alloying of Au and Pd. Thus, it is supposed that the temperature on the samples were temporarily increased to above the Au–Pd alloying point (1064°C).[16]

In order to check the reproducibility on the same samples, we again immersed these samples into D_2 gas in the same chamber, and then evacuated it. About 150 seconds after the start of pumping, we observed a second gigantic neutron burst of 0.06–0.09 mSv/h for 1–2 seconds followed by an explosive release of gas. After the pressure in the chamber was increased up to 1 atm with N_2, we again evacuated the chamber. Almost the same neutron emission and gas release were again observed about 150 seconds after the start of pumping. The second and third neutron bursts were recorded by the analog output of the neutron detector and are shown in Fig. 3.

We performed approximately 20 experiments with the same procedure as denoted above. Neither of the above-mentioned events was observed in any of those experiments. We also performed a few experiments replacing D_2-gas by H_2-gas and observed neither explosive gas release nor neutron emission. However, this does not mean that a mechanism responsible for the observed phenomena other than the fusion reaction itself does not exist in Pd:H systems, because the production of accumulation layers followed by biaxial bending of the samples is expected to be almost independent of the mass number of the hydrogen-isotope.

Here, it must be noted that all high-voltage (>200 V) power sources in the laboratory, except for the ion vacuum gauge, were off when the first, second and third neutron emissions described above were detected. We used batteries as the power source of the neutron detectors throughout the present experiment, and continuously confirmed the absence of a noise on the analog output of the detectors, for a few months since the beginning of the experiment. It must further be noted that, in order to calibrate the BF_3 neutron detector, we performed D^+-ion implantation into Pd:D at 50 to 200 keV just after the first and second neutron emissions. It was found that the measured neutron flux coincides with that measured by another neutron detector (Nuclear Enterprises Ltd.: NM2B) at various acceleration energies and dose rates.

Provided that event (1) results from the usual D-D fusion reaction, the energy of emitted neutrons is 2.5 MeV and/or 14.1 MeV. Then, the neutron dose of 0.1 mSv/h is equivalent to the neutron flux of 72 n/(cm^2·s).[17] Thus, the amplitude of the first neutron emission is roughly evaluated to be $(1-2)\times 10^6$ n/s by assuming the neutron emission from the samples to be almost independent of the angle. The amplitude of the second and third emissions is equivalent to $(0.6–0.9)\times 10^6$ n/s. The neutron



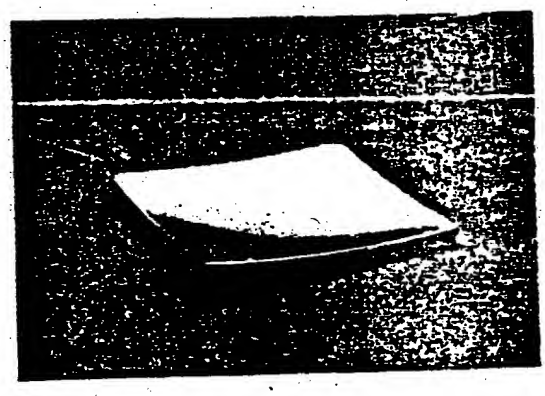


Fig. 2. A 3.0 cm × 3.0 cm palladium sample (thickness = 1.0 mm) after the third neutron burst and explosive release of D_2 gas. Top side is Au-coated surface at which alloying occurred after the first neutron emission.

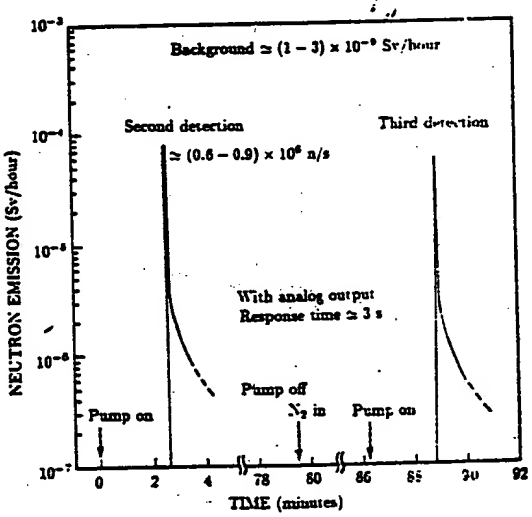


Fig. 3. The second and third neutron emissions as a function of time. The tailing behaviour after the neutron is detected is of no significance; it is only a characteristic of the analog output of the device.

larger than that reported by Fleischmann and Pons.[2] Here, it is noted that the background level for neutron detection was $\sim(1-3)\times 10^{-9}$ Sv/h ($\sim 10^{-3}$ n/(cm^2·s)) throughout the present investigation.

Furthermore, it can be considered that the gas released in event (2) is D_2 which was dissolved in the Pd samples, because atoms or molecules with a mass number of 4 were detected in great quantity in the residual gas. Here, it is noted that atoms or molecules with the mass number

thought to be caused mainly by explosive out-diffusion of D-atoms through the interface between Pd and a thin Mn–O film. Besides, the reason for the sudden excess heat production is still not clear. It may be strongly correlated to the decomposition of PdD_x ($x>0.6$) and subsequent release of D_2 gas, as argued by Pauling,[18] or to the lattice rearrangement due to the plastic deformation, as described by event (3).

Now let us consider the origin of the enhancement of the nuclear fusion rate observed in the present experiment. Kondo,[19] Sun and Tománek[20] and Wang *et al.*[21] have theoretically shown that the separation between hydrogen atoms is much larger than the value required for a significant fusion rate in the equilibrium. Therefore it is believed that the present observation should result from some nonequilibrium processes, for instance, a rapid change in the configuration of host Pd-atoms or defects so as to bring D-atoms much closer to each other than in the equilibrium sites.

One possibility for this is the "fracture" mechanism;[22-25] that is, an electrostatic field induced at the fracture or crack may accelerate the D^+-ions and cause nuclear fusion. Another possible mechanism is the host-lattice rearrangement due to sudden plastic deformation followed by dynamical "musical-chairs" motions of D-atoms as follows:

During the diffusion process, D-atoms are accumulated at the interface and form a thin layer of β-phase PdD_x ($0.6<x<1.0$), or an oversaturation phase with x larger than 1. This formation increases the lattice constant at this layer, and then gives a biaxial strain to the samples. The strain, in turn, enhances the out-diffusion of D-atoms to the same side of the surfaces (Gorsky effect). Therefore, these effects can give a cooperative cycle of positive feedback to increase the D concentration at that side of Pd surfaces.* The resulting catastrophic increase in the strain due to the accumulation of D-atoms finally produces a plastic deformation in the sample plates, as in event (3), and causes each host Pd-atom to rearrange rapidly. As a consequence, D-atoms are forced to move dynamically to attain new potential minima. In fact, the X-ray analysis for the samples after the third neutron emission has revealed that there were considerable degradations of Pd crystals without the β-phase at the expanded surfaces, while the Au-coated surfaces had no degradation and contained a slight amount of β-phase.

Here, we will conjecture that the rapid rearrangement of Pd-atoms can greatly increase the potential energy of D-atoms, by showing a simple example. Figure 4 indicates the calculated contour map of the empirical potential[26] for the H-atom in Pd. As shown in Fig. 4(a), both the octahedral (O)-sites and the tetrahedral (T)-sites, whose numbers are, respectively, 1 and 2 for one Pd-atom, give local minima without strain. As the biaxial strain parallel to the (110) plane is increased, the O-sites tend to become saddle points and no longer offer stable sites to hydrogen atoms, as shown in Fig. 4(b). In this case, the displaced T-sites become new local minima. Within such elastic deformation, it cannot be expected that D-atoms, which could have moved from the O-sites to the displaced T-sites, obtain energy high enough to give a high fusion reaction. However, at the very moment of plastic deformation, the Pd-atom rearrangement due to the production of defects can increase the potential

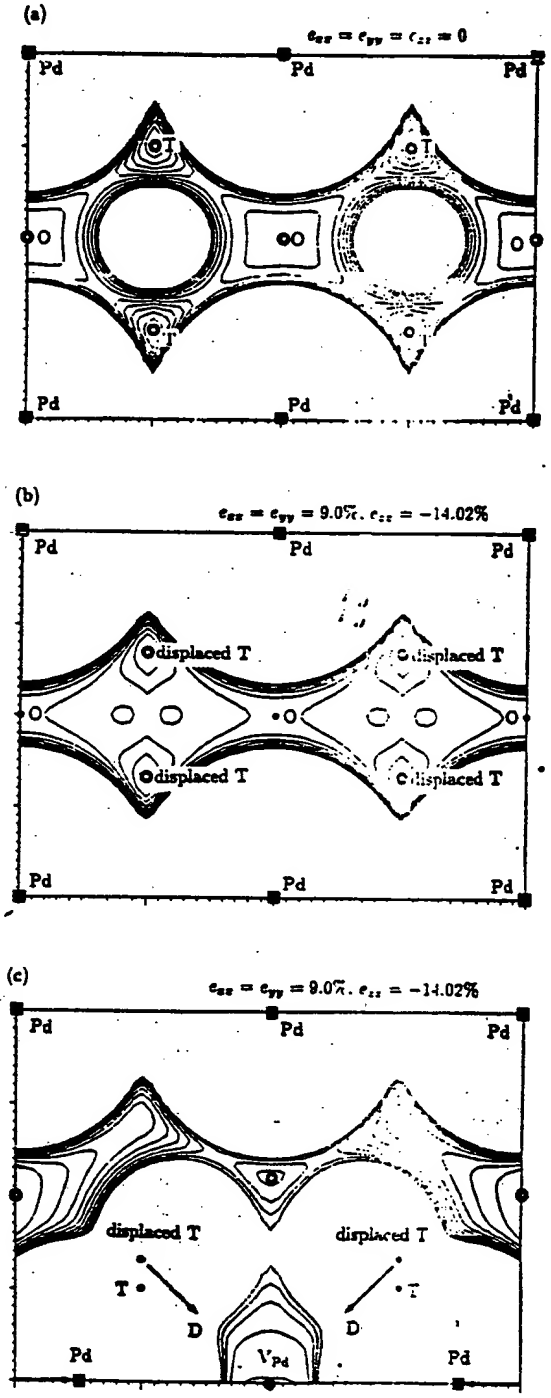


Fig. 4. Potential contour for the H-atom in the Pd (110) plane (a) without the strain, (b) with the biaxial strain ($e_{xx}=e_{yy}=9\%$) and (c) with a vacancy (V_{Pd}) and nearest-neighbor rearrangement (bond-shrink by 25%) as well as the biaxial strain, where the ⟨110⟩ direction is set to the z-axis and the contour step is 50 meV (200 meV for Fig. 4(c)). Shaded areas have energies larger than 5 eV (2 eV for Fig. 4(c)) from the potential bottom, and the open circles represent the

*The difficulty in reproducing the present experiment may therefore be due to the fact that the cooperative production of D accumulation layers at Pd surfaces critically depends on the characteristics of the surface barriers.

nitude at the displaced T-sites to the order of 10^{2-3} V, as schematically shown in Fig. 4(c) for the simplest lefect (a single vacancy). It can be easily shown that this lso holds for more complex defects such as edge or crew dislocations. Here, it must be noted that the umber of potential minima can be decreased for any ase. Therefore, at this time, the probability that D-toms having the kinetic energy of the order of 10^{2-3} eV ollide with each other will be increased significantly. fore detailed calculations will be necessary to check the alidity of the proposed model.

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Measurement of Neutron Emission from Ti and Pd in Pressurized D_2 Gas and D_2O Electrolysis Cells

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Experiments using high-efficiency neutron detectors have detected neutron emission from various forms of Pd and Ti metal in pressurized D_2 gas cells and D_2O electrolysis cells. Four independent neutron detectors based on ^3He gas tubes were used. Both random neutrons (0.05–0.2 n/s) and time-correlated neutron bursts (10–280 n) of ≤100-μs duration were measured using time-correlation counting techniques. The majority of the neutron burst events occurred at ~ −30°C as the samples were warming up from the liquid nitrogen temperature.

1. INTRODUCTION

The recent announcement by Flesichmann *et al.*,[1] that, excess heat and substantial neutron flux had been observed in Pd cathodes in electrochemical cells, stimulated numerous experiments, although several claims (for example, gamma rays from neutron capture) have been retracted.[2] Independently, Jones *et al*[3] observed 2.5-MeV neutron production at low levels during electrolytic infusion of D_2 into Ti and Pd electrodes, and discussed other means of creating non-equilibrium conditions, which might lead to "cold fusion." A replication of the latter experiment in the Gran Sasso Laboratory in Italy[4] provided confirmatory evidence for low-level 2.5-MeV neutron production. In addition, neutron emission has been reported in Ti subjected to pressurized D_2 gas and temperature changes.[5,6] We have measured neutron emissions at low levels in both electrolytic cells and in metals subjected to pressurized gases. In particular, we have observed the production of up to 300 n in bursts of ≤100-μs duration, as well as random or single neutron emissions.

We have measured both burst neutrons and random neutron emissions from a variety of sample types. The samples included cylinders of pressurized D_2 gas mixed with various forms of Pd and Ti metal chips, sponge, crystals, and powder. In addition, we have performed neutron measurements for electrolysis cells containing D_2O and cathodes of Ti, Pd, and V.

We are using four separate neutron detector systems operated in parallel experiments. The detectors all utilize ^3He gas proportional counters embedded in a polyethylene (CH_2) moderator. Three of the detectors are of the cavity- (well-) type, and one has an open channel for larger samples. The electronics are based on shift-register circuits[7] that give both the random and time-correlated neutron counting rates.

2. DETECTORS

Four similar detector systems were used in the present experiments to increase sample throughput and to

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Acoustical emission has been used for qualitative monitoring of cracking in the Ti samples. The sensor is a Dunegan/Endevdo acoustic transducer (Model D9203A-AD63) that is tuned to 150 kHz frequency and is attached to the outside of the sample bottle.

3. DATA SURETY

For low-level neutron counting and especially neutron burst counting, it is necessary to distinguish true neutron counts from spurious background noise. We have taken the following measures to assure that our burst events originate from neutrons:

- We use four separate detectors operating in parallel to pick up common sources of noise such as line voltage spikes, RF interference, cosmic-ray showers, and external room neutrons.
- We alternate dummy sample runs with the active sample runs.
- For System 3, we split the signal output to long (128-μs) and short (16-μs) gates and require that the gate count ratio be consistent with the detector die-away time (~50 μs).
- We collect singles counts, coincidence counts, and accidental counts and require that the three rates be consistent with observed neutron bursts.
- We detected the neutron bursts at a predictable time (2000–4000 s into the warm-up from liquid nitrogen, LN) and temperature (~ −30°C) for our first 12 bursts (samples Ti - 1 and Ti - 6) and many subsequent bursts.
- For sample numbers greater than Ti-17 we have added to System 3 a bank of Cd-covered ^{3}He tubes that measure only electrical noise and not neutrons. This acts as a veto for spurious electronic noise events. System 4 was upgraded with an external ring of eight ^{3}He tubes to monitor the inside/outside tube ratio to check for consistency with sample neutrons as compared to external source neutrons or electrical noise.

For System 3, we calibrated the gate fraction for instantaneous neutron bursts (spontaneous fission) using a ^{252}Cf source for which the ratio was 128-μs gate/16-μs gate = 3.18 ± 0.01. For the sum of several weeks of data collection in System 3, the long to short gate ratio was 3.2 ± 0.3 for the cosmic-ray background and 2.5 ± 0.4 for the sample neutron bursts. These ratios both agree statistically with the ^{252}Cf ratio and give additional evidence that the observed bursts are from neutrons. Cosmic-ray spallations give a source of instantaneous coincidence background neutrons, and the gate ratio was measured to be the same as a ^{252}Cf spontaneous-fission source.

Prior to the work reported in this paper, we operated detector System 1 and System 3 for 4 weeks measuring Pons-type[1] electrolysis cells. During these experiments, we observed no neutron bursts or excess random neutron emissions. In retrospect, these samples could be considered dummy samples.

Additional measurements were performed to ensure that environmental noise was not getting into the detector systems. The results of these tests were as follows: (1) no gamma-ray sensitivity up to 1 R/h, (2) the entire detector was cooled to −40° C with no change in performance, (3) no electrical noise pickup for noise generators (Telsa coils) placed directly into the detector cavity, (4) a long-term efficiency stability (precision) of 0.01%, and (5) no microphonic noise pickup for mechanical fracturing experiments or tests involving ultrasound in the detector cavity.

4. NEUTRON BACKGROUNDS

We performed four experiments to establish the source of our backgrounds: (1) we removed the CH_2 moderator from detector Systems 3 and 4 and covered the ^{3}He tubes with 0.4-mm-thick cadmium sheet; (2) for the normal detector configuration (System 3), we increased the sample mass (steel) six-fold and measured the increase in background; (3) we removed the neutron shielding from System 4 and measured the background rate at ground level; and (4) for System 2, we replaced the AMPTEK amplifiers with a conventional pre-amplifier plus multichannel analyzer to collect the 765-keV pulse-height spectrum from neutron capture in ^{3}He gas tubes.

4.1. Time-Correlated Counts

Our primary neutron burst results correspond to time-correlated counts. The time-correlated background counts are essentially all from cosmic-ray spallation neutrons originating in the detector body (CH_2 + Al) and the sample (steel + Ti). This was established by experiment number 1, for which the neutron efficiency is so small that the coincidence efficiency is negligible. For this experiment, the time-correlated counts were less than one per day.

For experiment number 2, the time-correlated background counts were 6.0 counts/h (6.5-kg steel bar), 2.3

Table II. Sample Materials

Sample identification	Gas	Pressure (psi) start-final[a]	Materials[b]
Ti-1	D_2	600-UN	111 g Ti sponge (2 g Ti crystals); 4.2 g Ti (6,6,2) chips
Ti-2	D_2	290-UN	~30 g Ti turnings (high temperature load)
Ti-3	D_2	290-UN	25 g Ti turnings (D_2 loaded at LN temperature)
Ti-4	D_2	400-UN	100 g Ti crystals, 100 g Ti sponge
Ti-5	D_2	600-UN	46.4 g Ti metal turnings
Ti-6	D_2	600-200	147 g Ti pieces, 17.4 g Ti powder, 4.6 g Pd powder, (D_2O electrolysis—22.8 g Ti sponge, 1.7 g Pd pieces)
Ti-7	D_2	580-14	33.3 g Ti sponge deuterided to ~Ti $D_{0.18}$
Ti-8	D_2	580-14	50 g Ti turnings, 4 g Ti sponge (D_2O elect.)
Ti-9	D_2	580-560	30 g Ti turnings and sponge (D_2O elect.)
Ti-10	D_2	580-UN	23 g Ti turnings, ~75 g Ti sponge ~4 g Ti crystals, 2 g Pd foils (all from D_2O elect.)
Ti-11	D_2	580-UN	82 g Ti powder, 10 g (90% Ti + 10% Pd) sintered powder
DH-1	$D_2 + H_2$	(425 + 425) − 842	30 g Ti alloy (6,6,2)[c] chips
DD-2	D_2	150-0	10 g Ti (6,6,2), 68 g Ti (6,4) chips
DD-3	D_2	830-816	10 g Ti (6,6,2), 68 g Ti (6,4) chips (deuterided during loading)
Ti-12	D_2	580-UN	14.8 g Ti sponge (D_2O elect.)
Ti-13	D_2	580-UN	10.3 g Ti (6,6,2) chips
Ti-14	D_2	550-UN	60 g Ti (6,6,2) chips
Ti-15	D_2	550-UN	50 g Ti sponge, 20 g Ti (6,6,2) chips
Ti-16	D_2	150-14 {520-100 500-150} refill	30 g Ti sponge, 34 g Ti-Pd-sintered powder, 45 g misc./ cathodes of Pd, Ti, Ni, Zr, V
Ti-17	D_2	40-14	60 g Ti (6,6,2) chips
DH-4	$H_2 + D_2$	196-0	80 g Ti (6,6,2) chips (deuterided during loading)
DD-5	D_2	40-0 (400-UN) refill	50 g Ti (6,6,2) chips
Ti-18	D_2	520-460	60 g Ti (2,3) chips

been used in electrolysis experiments of the Jones type.[3] Forty-two gas cylinder samples have been used in the experiments and 14 have yielded neutron emissions. Our attempts to run experiments using a single material component to isolate the neutron source have had limited success because of the intermittency of the effect. That is, the "right material" might still give a negative result because of variations in surface condition or some other feature required for the emission of neutrons. (Table II gives a listing of the contents of the gas samples measured through September 1989).

Three dummy samples (filled with air and Ti) and five H_2 gas cylinders were used for control runs. The stainless-steel gas cylinders were the same size and mass as for the normal samples. The Ti masses ranged from 50–200 g for the control cylinders. For many control runs, the same steel cylinder would be used for repeat experiments where the Ti was changed. Also, for the normal samples, the same steel cylinders were used for multiple samples where the Ti and gas fills were changed. Details on the H_2 gas control cylinders are given in Table II.

5.2. D_2O Electrolysis Experiments

In addition to the gas phase experiments, we have run four experiments using Jones-type[3] cells and electrolytes. Each of the experiments had six D_2O cells located in System 1. The anodes were gold foils and the cathodes were Ti, Pd, V, and Zr (foils, crystals, sponge, and sintered powder).

For one experiment, the electrolyte was D_2O mixed with the multiple ingredients described in Ref. 3. For the other three experiments, the electrolyte was an acidified (pH = 4) 10-g/L Li_2SO_4/D_2O solution. The currents and voltages were varied over the range from 0–4 A and 0–16 V, respectively. Sometimes the voltage was pulsed (700 ms on, 100 ms off). The data were collected in 1000-s or 2000-s time bins, and the experiments lasted for several

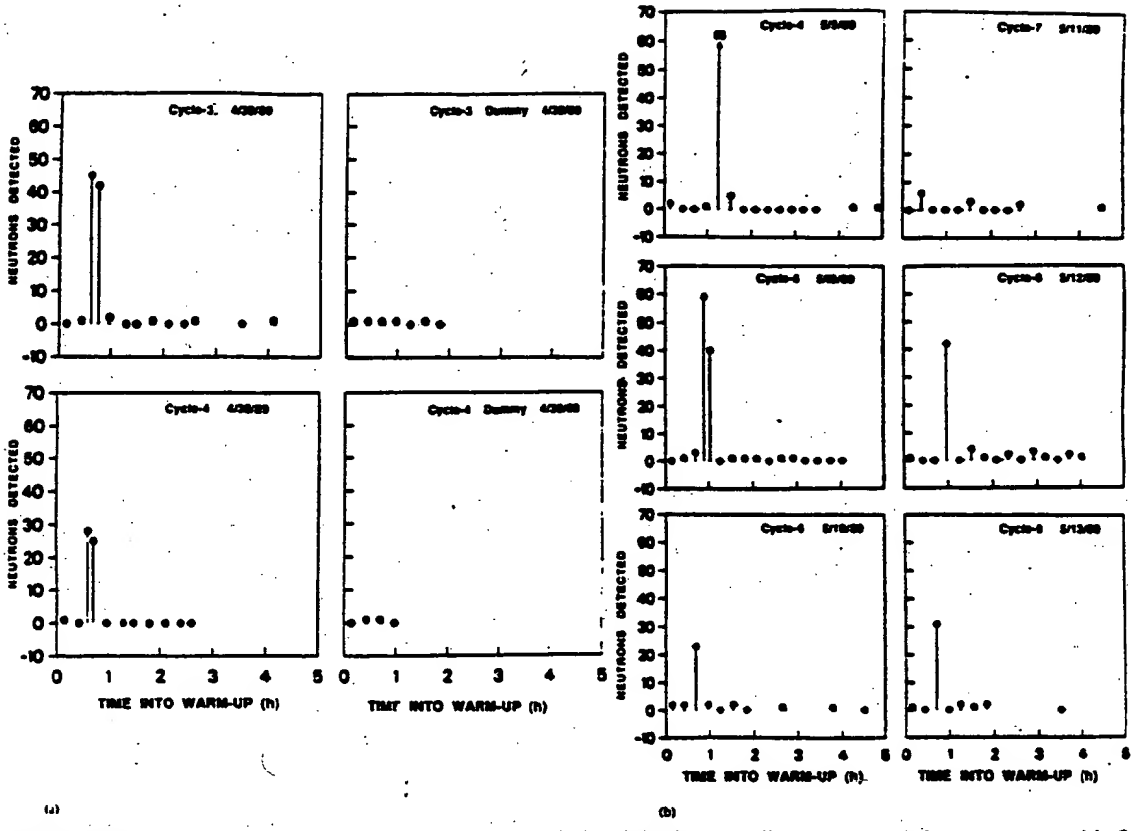

Fig. 1.(a) The combined coincidence results for the Ti-1 sample (left side) and the dummy cylinder (right side) that were measured in System 3. The dummy and the T-1 sample were measured alternating in time in the detector. Time zero represents the removal of the cylinder from the LN for both the sample and dummy. The ordinate corresponds to N, the number of neutrons detected in the 1000-s time bins. These neutron bursts were shown to arrive within a time of less than 100 μs. The average number of coincidence counts in the dummy runs was one count every 2000 s. The control counter (System 4) gave null results during the entire experiment. (b) The coincidence results, N, for six active cycles for sample Ti-6 measured in System 3. The neutron burst results mostly occur 2000–4000 s into the warm-up period. The ordinate N is the number of neutrons detected in individual bursts. The largest burst gave 85 neutron counts representing a source term of 253 n.

servations was approximately −30°C with a wide temperature distribution as shown in Fig. 2a.

The significance of the relationship between the temperature and the neutron bursts is yet to be established. It might be related to phase changes in the metal or to other stress conditions. If Ti metal is deuterided to a sufficiently high level, it has the possibility of going through a phase transition between 77–300°K. However, none of the samples that had been pre-deuterided at elevated temperatures gave neutron yields.

We also have observed bursts from a cylinder (DH-1) loaded with 30 atm of D_2 plus 30 atm of H_2 gas. The addition of the H_2 gas was motivated by the possibility of obtaining p + d fusion in future experiments and measuring the high-energy (5.4-MeV) gamma rays.

This sample gave no bursts during the warm-up from LN temperature; however, we have observed at least four neutron bursts from the cylinder at room temperature as shown in Fig. 3b.

We have recently run hydrogen gas control experiments with five samples loaded with H_2 gas in place of D_2 gas. There was no excess neutron yield from these five experiments over a period of several months. These cylinders are now serving as control cylinders for alternating runs with the sample cylinders. After 5 days of measuring the H_2 gas control sample Ti-31, the H_2 gas was replaced by D_2 gas and the sample was renamed Ti-31A. The refilled sample Ti-31A subsequently gave two large bursts during the warm-up from LN at −−30°C (see Table III).

6.1.2. Random Neutron Emissions

In addition to the burst-type results, we have measured random neutron emissions from several of the gas

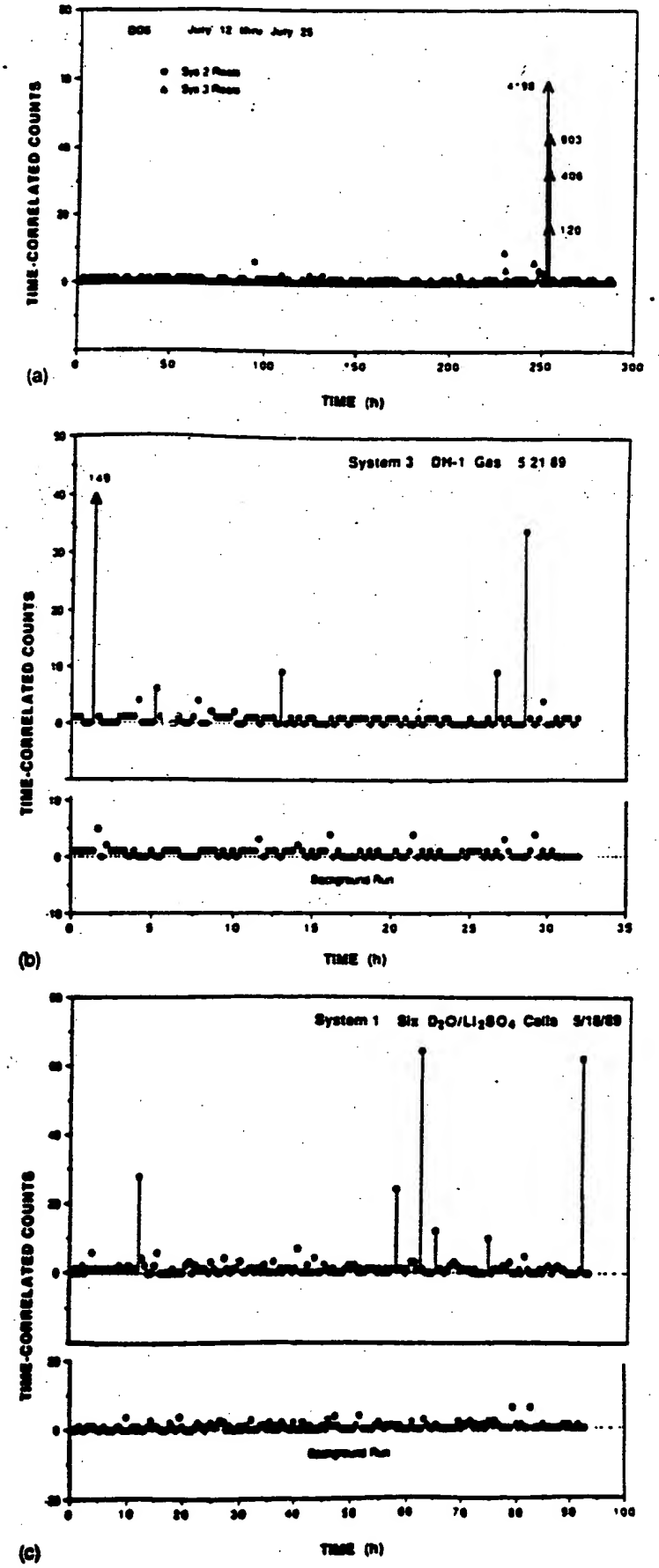

Fig. 3.(a) The number of coincidence counts R, in 2000-s time bins vs. measurement time for sample DH-5 measured in Systems 2 and 3. The large burst events at approximately 250 h occurred at a sample temperature between -100 and 0°C during the warm-up on LN cycle 6. (b) The number of coincidence counts R, vs. time for sample DH-1 (top curve) and the dummy cylinder (bottom curve). All of the bursts occurred at room temperature. The ordinate corresponds to the number of time correlated counts measured during the 2000-s time bins. The background coincidence counts result from cosmic-ray neutron bursts in the detector. The first sample burst occurred about 18 h after the first LN cycle. (c) The coincidence neutrons counts, R, vs. time for six D_2O electrolysis cells measured in System 1. The bottom data correspond to six D_2O dummy cells measured in the same detector immediately after the sample run was completed. The ordinate corresponds to the number of time-correlated counts R measured during the 2000-s time bins. The burst activity continued for several hours after cutting off the current at 71 h into the experiment. The control runs taken in Systems 3 and 4 gave no burst activity or change in background rates during either the sample run or the dummy runs. The largest burst corresponds to a source term of approximately 130 n.

cylinders. The electronics that we are using were designed to separate purely random neutron emissions from time-correlated bursts in which two or more neutrons emitted at the same time are considered a correlated event.[8] The results for sample Ti-1 are shown in Fig. 4.

Immediately following the Ti-1 overnight run, in System 4 the sample (Ti-1) was counted alternating between Systems 3 and 4 with the dummy in the opposite detector. These runs were for 4000 s each with two round trips in each detector for a total of 8000 s in System 3 plus 8000 s in System 4. Sample Ti-1 gave an excess of random neutron counts in both systems with a significance level in System 3 of 2.6σ and 3.6σ in System 4. The combined (both detectors) significance for Ti-1 was 4.3σ above the dummy background baseline. No temperature cycling was involved during this period.

Sample Ti-3 gave an excess random neutron emission during the 5-h period following the first LN temperature cycle. The average totals rate was 0.2594 ± 0.0034 counts/s for the 5-h period, which was 4.3σ above the dummy background baseline rate of 0.2413 ± 0.0025 counts/s that was measured for a 11-h period before and after the sample run. The adjacent control detectors gave a constant background rate during the sample and background time periods. Subsequent temperature cycling of this sample gave no random burst emissions.

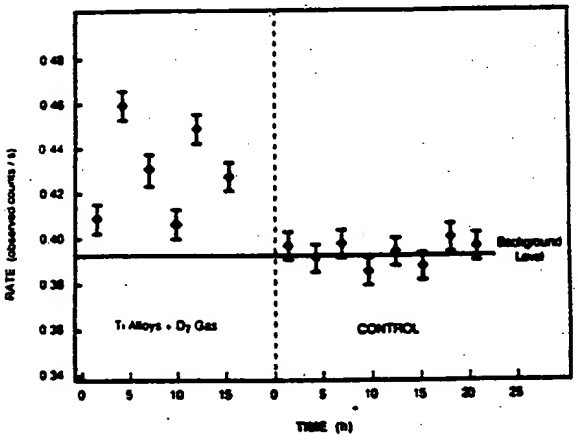

Fig. 4. The totals (random) neutron counting rate for sample Ti-1 measured in System 4 over a 17-h time period at room temperature after the first two LN cycles. The right-hand section of Fig. 3 corresponds to data for the dummy sample in System 4, and the time line is reset to zero when the dummy count starts. The data taken in the control counter (System 3) during the same two nights gave a constant background rate during the two nights. The average of the 17-h sample data was 0.4298 ± 0.0027 counts/s, whereas the average of 22 h of the dummy runs was 0.3943 ± 0.0022 events/s. The difference in the two average values corresponds to a 10.3σ significance level.

For the random neutron emission results, long counting intervals are required to statistically differentiate the low-level emission rates (0.05–0.2 n/s) from the background rate.

6.2. D_2O Electrolysis Results.

We performed three experiments with Jones-type[3] cells where each experiment involved six D_2O cells containing different cathodes of Ti, Pd, Zr, and V metal. While two experiments showed ~3σ results above background levels, the limited sensitivity in the random-counting mode precludes any definitive statement concerning neutron emission at this time.

A fourth experiment gave burst yields after running the current for about 12 h of electrolysis, and the bursts continued for several days as shown in Fig. 3c.

7. SUMMARY

We have observed both burst and random neutron emissions from 14 samples involved in 42 different experiments. Table III gives a summary of the results. Two different detector systems have been used to measure the random emissions and all four systems have detected the burst results. The individual burst results are as much as two orders of magnitude above the background levels.

Cosmic-ray neutron bursts are responsible for the coincidence background. Typical background counts are shown in Figs. 1,3, and 4 for the dummy runs. Some of the sample burst results could be large cosmic-ray bursts, but they should also be showing up during the background runs. The largest background burst that we have observed in the four systems over a 20-week period was 9 n detected (a source term of 30 n) in System 4. Samples Ti-1 and Ti-6 yielded neutron bursts at a predictable time into the experiment: all 12 neutron bursts occurred between 2000–4000 s into the LN warm-up cycle.

The results reported in this work do not define the neutron production mechanism. Several models have been proposed for the production of neutrons in the two types of experiments for which they have been detected; that is, electrochemical experiments and those in which various forms of Ti metals or alloys have been subjected to thermal cycling under D_2 gas at pressure. The possibility of particle acceleration caused by charge separation during a fracturing process has been suggested.[11–13] In support of the latter suggestion, both electron and positive

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Preliminary note

Helium production during the electrolysis of D_2O in cold fusion experiments

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INTRODUCTION

Our interest in the "cold fusion" process [1,2] was piqued by the apparent lack of systematic investigation into the composition of the gaseous products produced during the electrolysis of D_2O. A critical issue in determining whether or not the cold fusion process exists is the quality of the evidence concerning the composition of the gaseous products. The low intensity of neutrons has prompted proposals of other fusion processes such as $d + d \rightarrow {}^4He + \gamma$ [3] and $p + d \rightarrow {}^3He$ [4,5]. Accordingly, we report the results of experiments designed to detect helium in the effluent gases from electrolysis reactions at palladium cathodes while rigorously excluding possible helium contamination from other sources. The calorimetric electrolysis experiments reported here were performed at China Lake, and the analyses designed to establish the composition of the effluent gases were performed in Austin.

EXPERIMENTAL

The effluent gas from calorimetric electrolytic cells designed to detect excess enthalpy [6,7] was collected with the rigorous exclusion of air, and passed through an activated charcoal cryofiltration system (Fig. 1) to remove all gases except helium [8]. The first stage of the cryofilter acts as a cryopump to sweep any helium entrained in the effluent gas into the filtration system, while the second stage of the cryofilter removes any D_2 that gets past the first stage.

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0022-0728/91/$03.50

TABLE 1

Reference and detection limit samples

Sample	Contents	Mass spec results [a]	Conclusion
(1) 01/08/91	500 ml, vacuum & filled with N_2, 3×	No ^{4}He observed	N_2 contains no ^{4}He [b]
(2) 01/09/91 A-1	500 ml NWC [c] N_2 from gas discharge line, cell A	No ^{4}He observed	in spite of accumulation & surge into mass spec.
(3) 01/09/91 A-2	500 ml NWC [c] N_2 from gas discharge line, cell A	No ^{4}He observed	in spite of accumulation & surge into mass spec.
(4) 01/09/91 B-1	500 ml NWC [c] N_2 from gas discharge line, cell B	He observed at detection limit [d]	He accumulated then surged into mass spec.
(5) 01/09/91 B-2	500 ml NWC [c] N_2 from gas discharge line, cell B	No ^{4}He observed	in spite of accumulation surged into mass spec.
(6) 01/16/91 N_2	500 ml, vacuum & filled with N_2, 3×; round trip shipment	large amount of ^{4}He observed [e]	air freight shipment induces flask leakage
(7) 01/17/91 N_2	500 ml, vacuum & filled with N_2, 3×; round trip shipment	No ^{4}He observed	air freight shipment without leakage
(8) 8×10^{11} ^{4}He atoms	10 mTorr air in 500 ml vacuum	No ^{4}He observed	condensable gas needed to sweep ^{4}He into filter
(9) 8×10^{11} ^{4}He atoms	10 mTorr air in 500 ml N_2	^{4}He observed at detection limit [d]	^{4}He accumulated then surged into mass spec.
(10) 1.6×10^{11} ^{4}He atoms	10 mTorr air in 100 ml N_2	No ^{4}He observed	100 ml flasks not big enough for sampling
(11) 8×10^{11} ^{4}He atoms	50 mTorr air in 100 ml N_2	^{4}He observed large peak, long dwell [e]	more ^{4}He observed than expected

[a] Mass spectrometer, always at highest sensitivity.
[b] This result is an example of experiments that were performed routinely to test the N_2.
[c] NWC = Naval Weapons Center at China Lake, CA.
[d] Detection limit is approximately 2:1 signal to background ratio, mass spectrometer at highest sensitivity.
[e] Peak with large signal to background ratio, peak dwelled a long time in mass spectrometer, mass spectrometer at highest sensitivity.

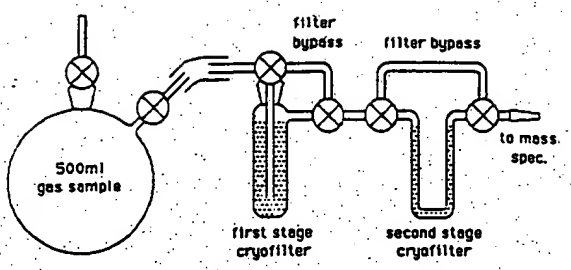

Fig. 1. The two stage activated charcoal cryofilter, designed to remove all gases except helium.

Strenuous efforts were made to avoid contamination of the effluent gas from the electrolytic cell with any external source of helium. A sketch of the cell and gas collection system is shown in Fig. 2. Two identical systems were always run simultaneously using calorimetric cells as described previously [7]. Connections between the cell, flask, and oil bubbler employed thick-walled rubber vacuum tubing. All connecting lines, as well as the cell, were flushed vigorously with boil-off nitrogen, which contained no ^4He (see Table 1), for at least 10 min prior to attaching a gas collection flask. Furthermore, the flasks were generally connected to the cell for at least two days of D_2O electrolysis before removal. The gas evolution rate was calculated to be 6.75 ml min^{-1} at 528 mA (200 mA/cm^2) and 700 Torr assuming ideal gas behavior; thus the 500 ml collection flask was further flushed with more than 19 times its volume of evolving D_2 and O_2 gases per day. Actual measurements of the gas evolution rate by the displacement of water yielded 6.75 ± 0.25 ml min^{-1} for cell A and 6.69 ± 0.15 ml min^{-1} for cell B. All solvent additions were made only after vigorously sparging the make-up D_2O with nitrogen for about 5 min. The D_2O was always added through the septum and stopcock into the cell using a gas-tight syringe (Hamilton No. 1005).

Commercially available argon gas, which might be considered as an "inert" atmosphere in these experiments, contained a substantial quantity of ^4He, but

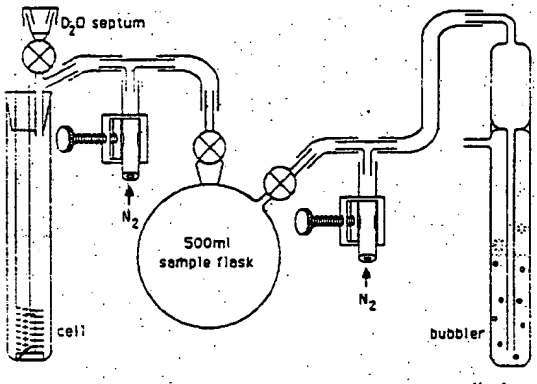

Fig. 2. Electrolytic cell with positive pressure gas discharge line used to collect samples of effluent gas.

b This result is an example of experiments that were performed routinely to test the N_2.
c NWC = Naval Weapons Center at China Lake, CA.
d Detection limit is approximately 2:1 signal to background ratio, mass spectrometer at highest sensitivity.
e Peak with large signal to background ratio, peak dwelled a long time in mass spectrometer, mass spectrometer at highest sensitivity.

nitrogen from liquid N_2 boil-off contained no detectable ^4He (Table 1). The palladium rod cathodes (Johnson Matthey, 99.96%, $A = 2.64$ cm^2, $V = 0.35$ cm^3) were wet polished with silicon carbide paper prior to use in these experiments. This surface treatment would likely remove any measurable helium contamination in the palladium [9]. Collection flasks were prepared in Austin for effluent gas collection at China Lake by applying a 10 mTorr vacuum (measured at the flask) followed by filling with boil-off N_2. This process was repeated three times per flask. The collection flasks (500 ml) processed by this method contained no detectable ^4He.

Mass spectral measurements were made using a Bell & Howell 21-491 mass spectrometer. The mass spectrometer had sufficient resolution to separate D_2 and ^4He easily when the mass peaks were displayed as analogue signals on an oscilloscope. After removing the air from the cryofilter by evacuating and flushing the filters with nitrogen multiple times, the evacuated filters were connected to the mass spectrometer, and the gas collection flask was attached to the filters using a short section of thick-walled rubber tubing; then the air in the rubber tubing was evacuated through the two filter bypasses as shown in Fig. 1. The filters were then cooled by immersion in liquid nitrogen for several minutes whereupon the stopcocks were manipulated to open the collection flask to the first stage of the cryofilter for approximately 10 s while the stopcock to the second stage remained closed. After allowing at least 1 min for adsorption of the effluent gas into the activated charcoal of the first stage cryofilter, the stopcock to the second stage cryofilter was opened. Concurrently, the valve controlling the evacuation of the ion source of the mass spectrometer was closed to enhance sensitivity by preventing rapid evacuation of the sample from the source. If helium had not been observed after approximately 3 min, then the inlet to the ion source of the mass spectrometer was valved off, and any helium diffusing through the cryofilter was allowed to accumulate between the filter and the valve. The opening of this inlet to the mass spectrometer surged any helium present into the source, thus enhancing the concentration of the helium to be observed. When operated in this manner, there is enough effluent gas in one 500 ml flask to perform two helium determinations should the results of the first determination be ambiguous for any reason. As demonstrated by samples 6–9 in Table 1, the detection limit for helium is approximately 8×10^{11} atoms of ^4He in the gas condensed into the cryofilter.

RESULTS

The reproducibility of our method for collecting gaseous samples and analyzing for helium is illustrated by the data presented in Table 1. No helium was detectable in routinely repeated experiments involving collection flasks filled with boil-off nitrogen (Sample 1). Collection flasks (500 ml) were then filled with boil-off nitrogen at Austin and shipped to China Lake where they were either connected to the gas collection system and flushed with boil-off nitrogen (Samples 2–5) or simply returned unopened (Samples 6,7). These flasks contained no detectable ^4He except in two cases (Table 1). We ascribe the miniscule amount of ^4He detected in Sample

TABLE 2

D_2O + LiOD electrolysis. The presence of helium in the effluent gas compared to the generation of excess power and heat

Sample	P_{ex}/W	$\Delta H_{out}/\Delta H_{in}$	Results [a]
(1) 12/14/90 A	0.52 [b]	1.20/1 [b]	^{4}He observed as large peak, long dwell; no ^{3}He [b]
(2) 05/05/75 B	0.46	1.27/1	^{4}He observed as large peak, long dwell [c]
(3) 11/25/90 B	0.36	1.15/1	^{4}He observed as large peak, long dwell; no ^{3}He
(4) 11/14/79 B	0.17	1.12/1	^{4}He observed at detection limit; no ^{3}He
(5) 04/29/65 A	0.24	1.10/1	^{4}He observed medium peak, some dwell; no ^{3}He
(6) 11/27/90 A	0.22	1.09/1	^{4}He observed as large peak, long dwell [c]
(7) 03/26/69 A	0.14	1.08/1	^{4}He observed at detection limit; no ^{3}He
(8) 01/18/37 A	0.07	1.03/1	No ^{4}He or ^{3}He observed
(9) 12/17/90 B	0.29 [d]	1.11/1 [d]	No ^{4}He or ^{3}He observed [d]

[a] Mass spectrometer, always at highest sensitivity.
[b] Current was 660 mA, all other experiments used 528 mA.
[c] No measurement of ^{3}He was made.
[d] The D_2O solution level of the cell was found to be excessively low resulting in an erroneous calorimetric result.

4 (01/09/91 B-1) and the large amount of ^{4}He detected in Sample 6 (01/16/91 N_2) to air leaks that may have occurred during shipment by air freight due to reduced atmospheric pressure in flight. Deuterium oxygen mixtures could not be shipped by air freight due to the explosion hazard. Thus the nitrogen standard Samples 2–7 in Table 1 represent worst case situations.

The ^{4}He detection limits (Samples 8–11 in Table 1), the purity of the flush gas (Samples 1–7), and our ability to exclude ^{4}He contamination from the air were determined concurrently with the analyses of effluent gas samples from China Lake. We believe that the analysis of effluent gas produced by the electrolytic cells are definitive. The results tabulated in Table 2 indicate that the effluent gases contained ^{4}He when electrolysis of D_2O produced significant excess heat and power. A second measurement was performed when the first measurement was ambiguous. The helium detection limit of our technique is approximately 0.14 W in terms of excess power (P_{ex}) or about 1.08/1 in heat ratios ($\Delta H_{out}/\Delta H_{in}$), with the calorimetry being accurate to 3% ($\pm 0.03/1$). The excess power of 0.14 W (8% excess heat) reported in Table 2 corresponds to approximately 2×10^{12} atoms of ^{4}He in a 500 ml flask as referenced to the 10 mTorr air in 500 ml of N_2 (Table 1). The excess power observed is roughly proportional to the concentration of helium in the effluent gas within the limits of experimental resolution. The calorimetric results reported in Table 2 were measured shortly before the removal of the gas collection flask; however, fairly constant values were obtained throughout the day.

In a preliminary experiment, dental X-ray films were positioned near the outer surfaces of two operating D_2 + LiOD electrolytic cells in an attempt to detect ionizing radiation. In both instances, the dental films were found to be significantly exposed when developed. It was not possible for hydrogen or deuterium to sensitize

TABLE 3

H_2O + LiOH electrolysis. Checking for ^4He in effluent gas

Sample	Results [a]
(1) 1/9/91 A-2	No ^4He or ^3He observed
(2) 1/16/91 A	No ^4He or ^3He observed
(3) 1/16/91 AA	No ^4He or ^3He observed
(4) 1/16/91 B	No ^4He or ^3He observed
(5) 1/17/91 A	No ^4He or ^3He observed
(6) 1/17/91 B	No ^4He or ^3He observed

[a] Mass spectrometer, always at highest sensitivity; any gas passing though the cryofilter was allowed time to accumulate and then surged into the mass spectrometer.

the film because the cells were completely sealed for effluent gas analysis. A cell containing H_2O + LiOH and producing no excess heat gave no exposure of the film in a similar experiment.

As a final experiment, the D_2O + LiOD in the electrolytic cells was replaced by H_2O + LiOH to serve as a control experiment. The H_2O + LiOH electrolysis, being conducted in an identical manner to the D_2O + LiOD electrolysis, is the best indication of our ability to exclude ^4He contamination from the air. However, fusion via the $p + d \rightarrow {}^3He$ pathway cannot be ruled out either theoretically [4,5] or experimentally [10] since our palladium electrodes likely retained some deuterium from the previous experiments. Although some unexplained excess heat effects were observed, no ^3He or ^4He was detected (Table 3). Furthermore, no exposure of dental X-ray films occurred in these H_2O + LiOH/Pd cells.

DISCUSSION

The use of the activated charcoal cryofilter removes the interfering D_2 and O_2 from the effluent gas allowing unambiguous observation of helium by mass spectrometry. Further. ^4He can be identified in the presence of D_2 because of its higher ionization potential; likewise ^3He can be distinguished from HD. As the accelerating voltage of the electron gun ionizer in the mass spectrometer is lowered, helium related peaks will disappear due to a decrease in ions produced, but molecules incorporating isotopes of hydrogen will continue to be ionized.

All of the relevant analyses were performed with the mass spectrometer at its highest sensitivity setting. Strenuous efforts to prevent helium infiltration due to air leaks were generally successful. Had gross air leaks occurred, helium would have been detected at concentrations several orders of magnitude above those observed.

The concentration of helium (^4He) observed in the gaseous products maintained an approximate correspondence to the amount of excess power measured in the electrochemical calorimetric cells (Table 2). This indicates that ^4He is produced at or near the surface of the palladium electrode rather than deeper in the bulk metal and that the preponderance of the helium escapes from the electrode and resides in

the effluent gas. Another study of helium in electrolyzed palladium tends to support this behavior [9].

Although the exact nature of the fusion reaction or reactions producing the excess heat effect is not known, the process

$$^2D + ^2D \rightarrow ^4He + \gamma + 23.4\ MeV \quad (1)$$

can be used as a basis for an estimate of helium production. For this fusion process, 1 W corresponds to the production of 2.66×10^{11} $^4He\ s^{-1}$. The highest excess power observed at 528 mA (0.46 W or 1.3 W/cm^3, Sample 2 in Table 2) would therefore produce 5.4×10^{14} atoms of ^4He in the time period required to fill the 500 ml collection flask with D_2 and O_2 gases (4440 s). It is apparent from Table 1 that this amount of ^4He would be more that two orders of magnitude above the detection limit for the analytical method used in this study. The large amount of ^4He observed in this experiment (Table 2) is likely to be within an order of magnitude of this theoretical estimate of helium production.

CONCLUSIONS

Our cold fusion experiments show a correlation between the generation of excess heat and power and the production of ^4He, established in the absence of outside contamination. This correlation in the palladium, D_2O system provides strong evidence that nuclear processes are occuring in these electrolytic experiments. The major gaseous fusion product in $D_2O + LiOD$ is ^4He rather than ^3He. No helium products are found in $H_2O + LiOH$ experiments. These results add to the accumulating evidence for cold fusion that involves 12 countries and more than 70 laboratories [11].

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NUCLEAR FUSION IN AN ATOMIC LATTICE : AN UPDATE ON THE INTERNATIONAL STATUS OF COLD FUSION RESEARCH

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Abstract

It is now two years since the first reports of the occurrence of nuclear reactions at ambient temperatures in deuterated metals such as Pd or Ti were published. "Cold Fusion" as this phenomenon has now come to be known has however become embroiled in intense controversy, with the scientific community becoming sharply polarised into "believers" and "non-believers" of this novel phenomenon. This ambivalence is primarily because of the non-reproducibility of the claimed results by many reputed research groups often using sophisticated experimental equipment. However as the present review clearly shows, a large number of laboratories in many different countries have now obtained very reliable experimental evidence confirming the generation of 2.45 MeV neutrons, tritium, charged particles, X-rays etc both in electrolysis experiments and in a variety of other D-plasma/ion beam loading experiments thereby confirming the nuclear origin of the phenomenon. These experimental results are such that they cannot be dismissed away as being "experimental artifacts" any more. It is understandable that the scientific community finds it difficult to accept a phenomenon that is not repeatable at will as "science". It would seem that the sporadicity of the results is due to some as yet unknown parameters which seem to be controlling the onset of nuclear phenomena in solid deuterated matrices. It has now become apparent that the phenomenon of cold fusion is highly complex. Although simple (d-d) reactions leading to the production of 2.45 MeV neutrons do seem to take place, that appears to be only one form of manifestation of the phenomenon. The excess heat measurements of Fleischmann et al have also been confirmed by now. The main indication at hand that it is of nuclear origin is the detection of He^4 in the off gases issuing from an electrolytic cell producing "excess power" as well as in some "spent" Pd rods which had produced "excess heat". Besides, the enormous magnitude of the energy released, upto a GJ/mole of Pd, is very dificult to be explained by any chemical mechanism. Theoreticians have come up with models which are beginning to explain many of the "puzzles" raised by the experimental observations. The fascinating new field of cold fusion has thus opened up new vistas in physics and technology.

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1. Introduction

Ever since the startling announcement in March 1989 by Utah scientists Fleischmann, Pons and Hawkins /1/ and shortly thereafter by Jones et al /2/, of the experimental observation of anomalous excess heat and/or fusion reaction products during the electrolysis of heavy water by means of Pd cathodes, there have been frantic attempts the world over to confirm this unbelievable phenomenon of "fusion in a bottle" or "cold fusion" as it has come to be known. Several laboratories such as the Texas A & M University /3,4/, Stanford University /5/, Case Western Reserve University /6/, Moscow State University /7/ and University of Florida /8/

reported obtaining positive results within weeks of the first announcement. The initial euphoria however soon turned sour when many other leading institutions such as Caltech /9/, Lawrence Livermore National Lab /10/, Sandia National Lab /11/, Chalk River /12/, Harwell /13/, Max Planck Institute at Munich /14/ etc failed to reproduce the "claimed" results of the original authors. Inspite of many groups reporting neutrons, tritium and excess heat production at the Santa Fe Workshop on Cold Fusion Phenomena (May 23rd-25th 1989) /15/, the overall impression which began to be formed in scientific circles was that cold fusion does not exist and the reported "evidence" was some peculiar "artifact" of the experiments. This was reflected in the final report of the US Department of Energy's 22 member Cold Fusion Panel submitted in November '89 /16/ which concluded that "the present evidence for the discovery of a new nuclear process termed cold fusion is not persuasive". They went on to surmise: "Nuclear fusion at room temperature of the type discussed in this report would be contrary to all understanding gained of nuclear reactions in the last half a century; it would require the invention of an entirely new nuclear process".

Meanwhile more "positive" results continued to pour in from laboratories such as Los Alamos /17/, Texas A & M University /18/, University of Minnesota /19/, Universidad Autonoma De Madrid /20/, Manne Seighbahn Institute of Physics /21/ at Stockholm and several different groups in Japan /22/. Besides electrolysis, deuterium gas loaded Ti /23/ and Pd /24/ targets both with /25/ and without /26/ application of electric fields have also indicated the occurrence of cold fusion reactions charting a new route for the exploration of the phenomenon of cold fusion. It was the National Science Foundation (NSF)/Electric Power Research Institute (EPRI) sponsored meeting on "Anomalous Effects in Deuterated Materials" held at Washington D.C during October 1989 /27/, in the presence of Edward Teller, that perhaps served as a turning point in the acceptance of cold fusion as a fact to be faced by the physics community although the number of firm "believers" remained small at that point of time.

In India experimental studies to verify the authenticity of the cold fusion phenomenon commenced immediately after the Fleischmann-Pons announcement with groups from the Bhabha Atomic Research Centre (BARC) /28/, Tata Institute of Fundamental Research (TIFR) /29/, Indira Gandhi Centre for Atomic Research (IGCAR) /30/ and Variable Energy Cyclotron Centre (VECC) /31/ reporting positive results. By December of 1989 a detailed description of the impressive work carried out at BARC during the first six months of the "cold fusion era" had been released as report BARC 1500 /32/. The experimental papers of this collection of notes have since been published in "Fusion Technology" /33/. Since the early BARC results are by now well documented and publicised, in the present update they will only be commented upon very briefly.

During the year 1990, there were two major international conferences devoted entirely to the subject of cold fusion which have helped to take stock of the progress of research in this field. The first was held at Salt Lake City late in March 1990 /34/ under the patronage of Fleischmann and Pons, to coincide with the first anniversary of their epoch making announcement, and emphasised calorimetry and excess heat studies. The other meeting which was hosted by Jones' group in October 1990 at the Brigham Young University in Provo, Utah concentrated on measurement of nuclear effects in deuterium/solid systems /35/. The present overview draws mainly from the proceedings of these meetings which together account for over a hundred papers, besides the very significant work reported during the last year from Japan. It is learnt that

there are presently over 50 groups involving over 250 scientists engaged in cold fusion research in Japan alone. In the USSR too significant results were obtained early on /36/. The status of cold fusion research in China was reviewed at a national level meeting held at Beijing in May 1990.

Bockris et al /37,38/ have presented a good summary of the status of cold fusion research as of mid-'90. Tibor Braun of Budapest has compiled a consolidated list of papers published in the area of cold fusion since the beginning /39/. Another good source of information is "Fusion Facts" /40/ which is a monthly digest of the latest reports on cold fusion. It is not the purpose of the present paper to give an exhaustive and thorough analysis of each and every published paper in this field so far but rather to give a broad overview of the cold fusion scene as it stands today, two years after it all began, highlighting the major new results published during 1990.

2. *Calorimetry/Excess Heat Studies in D_2O Electrolysis*

The simple electrolytic cell which was used by Fleischmann et al /1/ to demonstrate the production of excess power comprised of a Pd rod cathode and a Pt wire anode wound loosely around the cathode as shown in Fig.1. The electrolyte was a solution of 0.1 M LiOD dissolved in D_2O. The cell, made of a double walled vacuum jacketed dewar type glass vessel, was immersed in a large constant temperature water bath. Thermistor probes located both inside the cell and in the water bath helped monitor the cell thermal power output. A built in immersion type electrical resistance heater was used to calibrate the thermal response characteristics of the system under steady conditions. The input joule power dissipation rate was computed as (E-1.54) *I watts where E is the applied voltage to the cell and I the cell current in amperes. 1.54 accounts for the energy consumed in splitting D_2O into deuterium and oxygen and is referred to as the "thermoneutral potential" for this system.

As is well known by now, the initial pioneering paper of Fleischmann, Pons and Hawkins met with considerable criticism /41,42/. Some of the points raised by his critics were: (i) Excess heat was due to recombination of electrolytically generated D_2 and O_2; (ii) Inadequate mixing of the electrolyte gave rise to errors in temperature measurements; (iii) Inadequate control of water bath temperature could have produced erroneous results; (iv) Fleischmann and Pons' heat transfer computations were subject to both random and systematic errors; (v) No blank or control experiments were done; (vi) The gamma ray spectrum presented by the authors as evidence of neutron production was spurious. All these have now been systematically answered by Fleischmann and Pons in three different papers /43-45/. It is by now clear that their calorimetric measurements were in fact quite reliable and that they (along with more than a dozen other groups in the world) have indeed obtained excess power levels of about 25 to 30% over and above the input joule power dissipation rate.

Fleischmann et al have carried out an exhaustive and systematic study of the excess power generated as a function of Pd cathode diameter (1,2,4 and 8 mm dia) and current density (8 to 1024 mA/cm^2) (See Table I). In general they find that excess power scales near-quadratically with current density, with the 1 mm diameter cathodes generating more specific excess power (W/cm^3) than the higher diameter cathodes at a given current density. In their experiments 8 mm rods for example did not generate any excess power. At ~ 1A/cm^2 the 1 mm rods produced an excess power of ~ 1W for an input power of ~ 4 W. This corresponds to a specific excess power of over 100 W/cm^3 (or ~

8 W/g) of Pd. In Ref /46/ Kainthla et al have examined eight possible chemical mechanisms which can in principle contribute to "excess heat" and have pointed out that even if all these mechanisms were to operate simultaneously, not more than 3 W/cm^3 can be generated. An important conclusion to emerge from the pioneering work of Fleischmann and Pons is that there seems to be a threshold current density of about a 100 mA/cm^2 below which the excess heat production becomes negligible, at least in the case of D_2O electrolysis.

A new phenomenon noticed by Fleischmann and Pons since their first publication is that superimposed on the "baseline" excess heat, sometimes large "bursts" of excess enthalpy, 20 to 40 times the input power values (see Fig.2) are observed /45/. The event depicted in Fig.2 lasted for a duration of almost a fortnight. This type of sporadic heat excursions have however been seen only by a few other workers so far /47,48,49/. But the baseline excess heat which is directly correlated with the current density has been observed by many laboratories now /3,18,19,22,50-55/, inclusive of two independent groups from the Oak Ridge National Laboratory /56,57/. The impressive work of Appleby et al of Texas A & M University / 3,18/ was carried out using a very sensitive "microcalorimeter" and tiny Pd cathodes of only 0.01 cm^3 volume. It is noteworthy that several groups /49,50,56,57/ have now confirmed the production of excess heat using "closed cells", wherein the electrolytic gases are recombined insitu using a suitable catalyst, in contrast to the "open cells" used by many early workers including Fleischmann and Pons. This is relevant because doubts had been raised that perhaps the excess heat may have arisen from recombination of D_2 and O_2 in the case of open cell experiments.

The integrated energy generated during baseline excess heat runs is found to be as high as 1 GJ/cm^3 and in "heat bursts" 16 MJ/cm^3. While Fleischmann and Pons have conjectured that these phenomena must be a "volume effect" occurring over the whole bulk of the cathode, Appleby et al, Bockris and others have provided many strong arguments in favour of its being a "surface phenomenon".

A very significant experimental finding regarding He^4 production in electrolytic experiments has been reported in early '91 by Bush and his collaborators /58/. These investigators carried out a mass spectrometric analysis of the effluent gases issuing from the electrolytic cell of Miles et al which was earlier found to be generating excess power /55/. Rather than look for helium in the spent Pd rods like most other groups, these investigators analysed the effluent gases. They collected the off gases in 500 ml gas flasks taking great pains to eliminate possible contamination by air which would have given rise to false helium signals. For this purpose they flushed all flasks with "boil off nitrogen" for atleast 10 minutes prior to connecting to the electrolytic cell. They had earlier satisfied themselves that boil off N_2 did not contain any He^4 within the detection threshold of their mass spectrometer. The electrolytic gases collected in the flasks were first passed through an activated charcoal cryofilter system to remove all gases except helium prior to mass spectrometric analysis.

Several blanks from H_2O electrolysis were run to optimise the procedure and ensure that no inadvertant air leaks occur. Their He^4 detection limit was established to be 8×10^{11} atoms in the gaseous contents of a 500 ml flask. This corresponded to an excess power of 0.14 W or 8% of input joule power in their case. They observed large He^4 peaks at four different excess power levels in the 0.22 W to 0.52 W region and at detection limit on two occasions when excess power was 0.14 W and 0.17 W respectively. Their experiments have demonstrated

a clear correlation between the generation of excess power and production of He^4. The concentration of He^4 in the gaseous products maintained an approximate correspondence to the amount of excess power measured in the electrochemical cell. They have also concluded that the He^4 is produced at or near the surface of the Pd electrode rather than deeper in the bulk metal and that the preponderance of He^4 escapes along with the effluent gases. Significantly they found no He^3 in any of the electrolytic effluent gas samples. Ref /58/ details the arguments of the authors as to why the He^4 could not have come from the Pd cathode as prior contamination.

3. *Molten Salt Electrolysis Experiment*

At the Cold Fusion Symposium organised during the 8th World Hydrogen Energy Conference held in Honolulu in July 1990, Liaw et al of the University of Hawaii presented some very spectacular excess heat measurements obtained with a molten salt electrolytic cell /59/. Drawing upon several years of experimental experience at Stanford University with a similar system for loading hydrogen into Pd (in the context of hydrogen storage studies) they carried out electrolysis at temperatures of about 350 C to 400 C with a eutectic salt comprising LiCl and KCl in which a small amount of LiD was dissolved to act as the main current carrier. Since LiD dissociates into Li^+ and D^-, in this cell Pd or Ti was deployed as anode. An electrical heating tape of 100 W capacity wound outside the Al vessel containing the electrolyte served to keep the salt molten. The entire set up was housed inside a glove box in an oxygen free dry argon atmosphere. Using a 0.5g button of Pd as anode and a consumable Al cathode they measured, after several days of precharging at very low currents, excess power levels as high as 25 W for an input cell power of just 1.68 watts, representing a power gain by a factor of ~15 (see Table II). The excess power in this experiment increased near-linearly with current density. At three current densities in the range of 290 to 692 mA/cm^2, the excess power episode lasted for almost 4 days generating in all ~5 MJ of energy (see Fig.3). The experiment was terminated only because the LiD was exhausted in the electrolyte. The authors have cited the total absence of oxygen in the electrolyte ("reducing environment") as the prime cause for its superior performance. This helps eliminate formation of hydrogen impeding oxide layers on the surface of the electrodes.

The Pd button used in this experiment when analysed by mass spectrometry was found to contain 4×10^{10} atoms of He^4, upto 14 sigma over that in a control sample of Pd taken from the same stock /60/. This quantity of helium is about seven orders of magnitude lower than that expected on the basis of the 5 MJ of integrated excess energy produced by the 0.5g Pd sample. Liebert et al have suggested (and it has now also been confirmed by Bush et al /58/ recently) that most of the He^4 produced escapes from the PdD_x matrix. Inspite of it the result is significant to the extent that it probably represents the first instance when He^4 has been found unambiguously in any electrode which has produced excess energy in an electrolytic cold fusion experiment.

The authors have also reported /59/ measuring excess heat levels of upto ~100% with a titanium anode but there was considerable fluctuation in the excess power output even at constant current density in that experiment.

The importance of the molten salt electrolysis experiment with Pd anode lies in the fact that the specific excess power generated, namely 25W/0.5g or 50W/g is already several times that of the UO_2 fuel elements of an Atomic Power Station. For example for the Rajasthan Atomic Power Station (RAPS), the specific power is 15W/g while for a Light Water

Reactor (LWR) the corresponding value is ~ 20 W/g. Since the densities of UO_2 and Pd are 10g/cm^3 and 12g/cm^3 respectively, the power density in the Pd fuel of the molten salt cold fusion cell works out to 600 W/cm^3 which is 4 times the 150 W/cm^3 of RAPS fuel or 3 times that of an LWR. (If an LWR or one of the RAPS reactors were to be operated at 600 W/cm^3 of fuel, it would result in a core melt down incident!) Likewise the integrated energy yield of this cell which was > 1 GJ/mole of Pd, corresponds to ~7 fusion reactions per 1000 (d-d) pairs. For RAPS fuel the fissions per 1000 heavy atoms of the fuel element is also about 7 at its average burn up level of 7 MWd/Kg of UO_2. Thus even within 3 days of operation of the molten salt cell, the specific nuclear reaction yield of the Pd anode has equalled that of a CANDU type nuclear power plant. Had the LiD stock lasted, it may well have exceeded this performance. Needless to stress, specific energy yields of GJ/mole of Pd cannot be explained on the basis of any non-nuclear phenomenon. All this is pointed out only to emphasise the fact that cold fusion is not to be treated as an academic curiosity but deserves to be given the respect due to a prospective new source of energy which has already matched (if not exceeded) the performance of a present day nuclear power plant! This remarkable experiment has been highly acclaimed by the cold fusion community and several advanced institutions in the world inclusive of the Oak Ridge National Laboratory (USA) and BARC, have initiated efforts to try and reproduce the results.

4. *Tritium Production in Electrolysis Ex periments*

Right from the inception of the cold fusion frenzy, efforts have been underway in many laboratories /37,38,61/ including BARC to establish the nuclear origin of the phenomenon in an unambiguous manner and hence an intense search was on to detect the production of neutrons and /or tritium from electrolytic cells. Texas A & M University /4/, BARC /62/, and Yang et al of Taiwan /53/ are some of the well known groups to have reported detection of large amounts of tritium during the electrolysis of D_2O with Pd cathodes. Many other laboratories inclusive of Los Alamos /63/ have also obtained clear cut evidence for tritium generation but at a lower level. Ref /62/ gives details of over 20 seperate experiments conducted at BARC wherein excess tritium was measured. Of these in 11 experiments, which includes one result from the Indira Gandhi Centre for Atomic Research (IGCAR) in Kalpakkam (see Table III), both neutrons and tritium were produced. The most interesting outcome of the BARC experiments is the observation that the neutron-to-tritium yield ratio is significantly smaller than unity by almost 8 orders of magnitude i.e. it is as small as 10^{-8}. This finding has since been corroborated by many other groups around the world /20,64,65/ and represents one of the many "puzzles" of the cold fusion phenome non (since in the (d-d) reaction it is well known that the branching ratio for neutron and tritium production is almost unity). But as this aspect has been well discussed in the BARC papers / 28,32,33,62/ it will not be dwelt upon further except for one important aspect, namely the "simultaneity" of generation of neutrons and tritium. Out of the 11 experiments in which neutrons and tritium were detected in atleast 3 instances where frequent sampling of electrolyte was resorted to it was noticed that the tritium level in the electrolyte jumped immediately after detection of a neutron burst (See Figs. 4 & 5). Similar observations have also been made by at least two other groups notably Sanchez et al of Spain /20/ (see Fig.6) and Gozzi et al /64/ of Italy. The importance of this will be appreciated if viewed in the context of the so called "Wolf episode" of the Summer of 1990.

Kevin Wolf of the Cyclotron Institute of the Texas A & M University created a sensation

when he claimed that he had found significant levels of tritium in one virgin Pd wire procured from the market /66,67/. It is worth noting here that Pd membranes are supposedly used to seperate tritium from its decay product He^3 in nuclear weapons establishments of advanced countries and it is alleged that some of this recycled and contaminated Pd probably finds its way into the open market. Wolf "found" 10^{11} to 10^{12} atoms of tritium in 3 samples each of 1 cm long wire (out of 45 such samples) taken from one lot of Pd received from one manufacturer namely M/s Hoover Strong Co. of USA. However this firm has since clarified that their manufacturing process is such that it is "impossible" for any tritium to remain in the Pd after the tortuous treatment to which it is subjected. In any case Wolf's "finding" was immediately seized by the skeptics of cold fusion as "proof" of their long standing "contention" that the significant quantities of tritium measured by cold fusion researchers in many different laboratories the world over was due to the sudden release of tritium present as "spot" contaminant in the Pd electrodes /68/. Meanwhile the National Cold Fusion Institute of Utah has carried out a systematic analysis of over 40 samples of virgin Pd procured from three different manufacturers inclusive of M/s Hoover Strong Co. using a microdistillation technique which is devoid of chemiluminiscene interference effects and has found no tritium contamination whatsoever in any of the market samples /69/. Independently Storms and Talcott of Los Alamos have carried out an electrolysis experiment using a Pd cathode intentionally preloaded with tritium /70/. They find that most of the contaminated tritium goes directly into the gas stream rather than into the electrolyte. In the context of Wolf's "finding" of tritium in virgin Pd, the simultaneous generation of neutrons and tritium discussed earlier acquires great significance /71/. Even Wolf has conceded that more such simultaneous observations of neutrons and tritium would confirm the nuclear origin of tritium /66/. Besides how can one explain the tritium and tritons (see Secs. 9 & 10) seen by several different groups in the gas/plasma loaded titanium samples, on the basis of contamination since titanium is never used for the seperation of t & He^3? Thus by the end of the Provo meeting of October 1990 the "accusation" that contamination is the cause of tritium observations in so many different countries has been virtually rejected /72/.

5. *Neutron Yield Characteristics of Electrolytic Cells*

Jones and his collaborators were the first to report /2/ a steady but low rate of neutron production during the electrolysis of D_2O using Ti(or Pd) cathodes. They measured the energy of these neutrons to be close to 2.45 MeV and inferred therefrom that (d-d) reactions occur within the cell, presumably in or on the surface of the cathodes. Their experiments yielded an estimate for the absolute magnitude of (d-d) reaction rate to be in the range of 10^{-23} to 10^{-20} fusions/d-pair/s /2/. Other groups who have since observed similar low level ("Jones level" as it has come to be called now) steady neutron yield are from Italy /73,74/, Argentina /75/, USSR /76/ and Japan /77/. The Argentine group carried out their experiment in a submarine (non-nuclear) 50 m under the sea, in order to reduce their background neutron count rate to a level as low as 0.001 cps /75/. As noted already, many other groups at BARC /33,62/ and elsewhere /20,21,78-80/ have however observed neutron production in the form of bursts (see Figs 4,5 & 6) rather than as a steady output. In these experiments the burst neutron production phase was found to last for a period ranging from a few minutes to several hours and at times even for several days, altogether stopping thereafter. Table III indicates the duration of the "active life" of the neutron production phase of the BARC cells.

Several researchers have observed that pulsing the cell current between a high and a low value improves the chances of neutron production. Interestingly atleast two groups have reported observing neutrons from a Pd-D_2O cell after the cell current was switched off /33,81/. These observations indicate that creation of some sort of non-equilibrium condition within the cathode helps induce the occurrence of nuclear reactions.

Arata and Zhang of Osaka have pursued this approach further and have discovered an intense "on-off effect" during the electrolysis of D_2O using a large (20 mm dia x 50 mm long) Pd cathode which resulted in the generation of intense bursts of neutrons /82/. They have shown that their "on-off effect" is tens of times stronger than the weak on-off effect induced by current pulsing mentioned earlier. They have exploited the temperature-loading characteristics of PdD_x and the high mobility of the deuterium in the Pd lattice, to make the Pd cathode to absorb and exhaust deuterium in a controlled manner. The essence of their argument is brought out by the hysterisis curve characterising deuterium absorption/desorption with temperature of the Pd sample (See Fig.7). They have argued that this property, coupled with the fact that deuterium absorption in Pd is exhothermic while desorption is endothermic is what is responsible for the "on-off effect". By raising the temperature of the water bath in which their electrolytic cell was immersed to levels close to 90 C they observed that the Pd cathode temperature started oscillating on its own between 80 C and 110 C with a period of approximately 10 to 20 mins. In one experiment the phenomenon occurred 50 times during a 20 hr period. This behaviour caused the rapid movement of deuterium into and out of the lattice leading to the occurrence of (d-d) nuclear reactions. Over 10 intense neutron bursts (or "avalanches") occurred during one such month long experiment /82/. The authors have reported that each avalanche lasted between 30 min to 40 hr, the maximum number of neutrons produced being as high as 10^{13} per event. From their experiments Arata and Zhang have concluded that the secret of success of neutron production in electrolysis of D_2O is use of a massive Pd cathode (20 mm dia x 50 mm long) rather than Pd rods of a few mm diameter recommended by Fleischmann et al for obtaining excess heat.

6. *Observation of a 4 to 6 MeV Energy Neutron Component in Electrolysis*

As noted earlier Jones et al /2/ were the first to establish that the neutrons emitted in cold fusion cells had an energy corresponding to 2.45 MeV, thereby giving the first clue that (d-d) reactions are the source of these neutrons. Many other groups have since independently measured and confirmed that the energy of cold fusion neutrons is indeed 2.45 MeV /67,74,77/.

Recently Akito Takahashi and his collaborators of Osaka University have obtained clear cut evidence for the presence of a 4 to 6 MeV energy neutron component besides the 2.45 Mev neutron peak in an electrolysis experiment (See Fig.8) /83/. They have cited this as proof of occurrence of the 3 body reaction $3D \rightarrow d + \alpha + 23.8$ MeV, using the "excitation-screening model" developed by Takahashi. According to his explanation the 15.9 MeV deuterons released in such 3D reactions will give rise to neutrons in the 3 to 7 MeV region during their slowing down in the PdD_x lattice. Takahashi admits that at a time when physicists find it difficult to accept the occurrence of even 2-body (d-d) fusion reactions in solids, conceiving of 3D fusion reactions postulated by him is an understandably arduous task.

It is noteworthy in this context that Iazzi et al of Torino (Italy) /84/ have also obtained results from D_2 gas loaded Ti shavings experi-

ments (see Sec.9) which indicate the presence of a 6 to 7 Mev energy neutron component besides the 2.45 MeV peak.

7. *Charged Particles in Electrolysis Experiments*

Taniguchi et al of Osaka have carried out an electrolysis experiment with a 10 um thick copper foil coated with Pd which formed the cathodic base of their cell (LiOD or LiCl + D_2O solution, Au anode) /85/. Below the cathode foil was a surface barrier detector. In 6 runs out of 23 they measured charged particles of energy less than 2.1 MeV energy after a charging time of several hours to a few days. The charged particle counts continued for several days at times (See Fig.9). They have argued that 3 MeV protons produced in (d-d) reactions while passing through the 10 um thick Cu-Pd foil will emerge with an energy less than or equal to 2.1 MeV, while 1 MeV tritons or 0.82 MeV He^3 if any are present will not be able to penetrate the full thickness of the cathode foil.

8. *Evidence of X-rays in Electrolysis*

Stan Szpak of the Naval Underwater Systems Centre at San Diego (California) has carried out a very interesting experiment which demonstrates that low energy X-rays are generated at the Pd cathode during electrolysis of D_2O /86/. He used a Ni mesh cathode and a Pt anode. The electrolyte was 0.05M $PdCl_2$ + 0.3M LiCl. Very close to the Ni mesh was a Polaroid film sealed in a light tight and water tight packing. After several hours of electrolysis the film on developing showed an impressive chequered pattern identical in image to the Ni-mesh. Presumably in the initial stages of electrolysis Pd gets deposited on the Ni mesh and in later stages gets loaded with deuterium which eventually supports anomalous nuclear reactions resulting in the generation of low energy X-rays.

Ref /58/ reports that Miles and his coworkers have also observed significant fogging of dental X-ray films positioned near the outer surfaces of two operating D_2O - LiOD electrolytic cells. An H_2O-LiOH cell did not cause similar fogging.

9. *Burst Neutron Emission From Gas Loaded Titanium Turnings*

At least a dozen independent groups / 17,23,73,84,87-92/ have so far carried out such experiments successfully involving the loading of deuterium gas into Ti lathe turnings (or chips) contained in a deuteriding bottle following high temperature (200 to 800 C) degassing under vacuum. This technique which was first suggested by Scaramuzzi of Frascati /23/. has since been substantially improved by the Los Alamos /17/ and Brigham Young University /81/ teams. The novel feature of these experiments is the use of liquid nitrogen (LN) to subject the TiD_x chips to repeated cooling - warm up cycles. A high efficiency neutron detector system comprising a large number of He^3 or BF_3 neutron detectors embedded in a hydrogenous moderator is employed to measure neutron output. It has been observed consistently by all the twelve groups that neutrons are invariably produced during the warm-up phase following a cooling cycle when the temperature of the chips is in the sub-zero range (-60°C to 0°C) (See Fig.10). From the known efficiency of neutron detection it has been established that between 30 to 300 neutrons are typically produced in each burst from the bottle as a whole. One or two groups have made preliminary measurements of tritium generation in such experiments by degassing and recombining the extracted deuterium gas back into D_2O and analysing it for tritium content. Zelensky et al of Kharkov /92/ appear to have independently developed and demonstrated this method as early as in April 1989 with the difference that they used an ion-implantation technique to load deuterium into metallic

titanium samples. Zelensky et al who monitored neutron output while steadily increasing (1 to 3 C/s) the sample temperature observed a very interesting double peak, one at -30 C and a second at 600 C (See Fig.11).

Similar deuterated chips experiments have also been carried out by us at BARC recently /93/ with the variation that the TiD_x chips were as such dropped into a canister containing liquid nitrogen. We measured the tritium production by directly counting the LN treated chips using beta and X-ray detectors. In earlier BARC studies /94/ it was shown that the 18.3 KeV (maximum energy) beta particles released during the decay of tritium (12.3 yr half life) excites the K - alpha (4.5 KeV) and K - beta (4.9 KeV) characteristic X-rays of titanium and this serves as an excellent tool to detect the presence of tritium. The BARC groups have also pioneered the use of the technique of autoradiography for studying cold fusion targets. Using these techniques it was found that < 1% of the several thousand TiD_x chips treated in LN had generated MBq levels of tritium. The main outcome of this work is the finding that not only is the anomalous fusion reactions found to take place in only a very few chips, even in those chips its production is restricted to a small number of selected localised "hot spots" only (See Fig.12) /89,93/.

10. Charged Particles from Gas Loaded Titanium Foils

Ed Cecil from the Colorado School of Mines has been successful in measuring the emission of charged particle bursts from deuterium loaded thin titanium foils which were subjected to liquid nitrogen cooling - warm up cycles /95/. The foils (0.1 mm thick) were prepared on a lathe using a broad cutting tool (>10 mm wide) much like the shavings obtained while sharpening an ordinary lead pencil. The shavings were vacuum annealed for 2 hours at 700 C and loaded with D_2 gas (2 atm, 1 hr). They were then gently flattened out and clamped onto an SS backing using a ring type washer such that a surface barrier detector could view the central part of the foil for measuring charged particle emissions. The SS holder in turn was mounted on a copper cold finger in such a manner that the temperature of the foil could be cycled between -180 C (LN) and + 20 C. Cecil's group observed bursts of high energy events spanning the 2 to 5 MeV band. When a 13.2 um thick Al foil was used to cover one half of the surface barrier detector, pulse height decreased as expected resulting in a double peak being seen. 12 samples out of 26 gave bursts; there were in all 24 bursts in 56 days. The burst duration varied from 1 to 100 mins (See Fig.13). Most of the bursts were observed 6 to 10 hours after removal of LN cooling. No such bursts were observed with hydrogen loaded foils. Species identification plots indicated that the observed charged particles were most probably tritons. The present experiments are a continuation of the preliminary work reported by Cecil et al /96/ at the Santa Fe meeting. In the earlier studies they had used an ion implantation method to load deuterium. They have also attempted to determine if passage of a current along the length of the deuterated foil would have any beneficial effect on charged particle emission; so far they have not been able to establish conclusively that a definite correlation exists between these. The results of Cecil's triton measurements compliment the neutron and tritium measurements on deuterated titanium samples described in the last section.

11. Charged Particles from Ion Beam Loaded Ti Foils

George Chambers and others of the Naval Research Laboratory of Washington D.C, have reported /97/ the detection of 5 MeV triton bursts from 1 um and 3.8 um thick Ti foils bombarded with 300 ev energy deuteron beams

in a vacuum chamber. They used an ECR type ion source. Only virgin Ti foils gave results, that too about 30% of the time. They never obtained results with either Pd foils or with predeuterated titanium i.e. TiD_x samples. When the bias to the charged particle detector was turned off, the pulse height dropped to 3.5 MeV as expected (due to decrease of effective depletion layer thickness in the detector). The most interesting part of their results is that the charged particles were of 5 MeV monochromatic energy, clearly ruling out (d-d) reactions as the source of these tritons, since in a (d-d) reaction one expects either a 0.8 MeV He^3 nucleus or a 1 MeV triton or a 3 MeV proton. 5 MeV tritons can however be explained on the basis of 3D reactions, surprisingly in conformity with the conclusions of Takahashi based on the 4 to 6 MeV energy neutron component observed by him in D_2O electrolytic cell experiments discussed in Sec.6 of this paper.

12. *Precursor to Charged Particle Emission from Gas Loaded Pd*

A 14 member multi-institute team from Beijing led by X.Z. Li of Tsinghua University has reported /98/ observation of precursor emission in the form of some electromagnetic radiation, presumably in the UV to soft X-ray region, prior to the production of charged particles from a D_2 gas loaded Pd foil. They used CaF_2 TLD detectors for the soft X-ray detection and CR-39 track detectors (SSNTD) for registering charged particles. The CR-39 detector on chemically etching showed clusters of charged particle tracks at many locations. They found that H_2 loading also gave TLD signals but no charged particle tracks giving credence to their suspicion that "electromagnetic radiation might originate from electrons which are transiting from state to state when palladium are filled with hydrogen or deuterium". They have further conjectured that "these photons must be in the 10 eV to 3 KeV region since the electron should approach to an orbit similar to that of Muons in order to screen the coulomb barrier effectively" /86/. One of the interesting findings reported by them is that Pd samples cleaned with acqua regia never gave any charged particles. Subsequent Auger Electron Scanning Probe analysis indicated that these Pd samples had significant quantities of chlorine on their surface. The inhibiting role of chlorine in suppressing the generation of charged particles is not yet understood. (This reviewer has learnt that these experiments have since been successfully repeated by two separate groups at the Brigham Young University recently /99/.)

13. *Solid State Cell Experiments of Los Alamos*

Claytor et al of Los Alamos have continued to develop their "solid state cell" /25/ concept which they first reported at the NSF/EPRI Workshop of Oct '89 /27/. In these cells a packed bed of alternate layers of Pd and Si powder is mounted between a pair of electrode plates (See Fig.14) in a pressurised (8 bar) D_2 gas atmosphere and an intermittent current passed through this solid state cell by application of a pulsed high voltage (1.2 to 2.5 Kv, 100 pulses, pulse width > 150 us). 8 out of 30 cells have so far produced excess tritium (greater than 3 sigma above background levels). At least one cell (cell # 2) produced both neutrons and tritium (6 MBq), the neutron-to-tritium yield ratio being 3×10^{-9}. At the Provo meeting Claytor reported that since the last few months, they have been investigating the use of Pd metal foils (Johnson and Matthey) in place of Pd powder and this has considerably improved the reproducibility of results. The tritium activity, as measured in the gas stream, is now "reproducible" being on the average ~20 Bq/hr.

14. *Neutron Production in a Pd Surface Barrier Plate*

Yamaguchi and Nishioka of NTT labora-

tories, Tokyo have demonstrated a novel technique for inducing anomalous nuclear effects in a Pd surface barrier device /100/. This technique which is based on Metal Insulated Semiconductor concept uses a thin MnO film deposited on one face of a deuterium loaded Pd plate, thereby providing a surface barrier for ionic transport of deuterons. The other face of the Pd plate is coated with a thin impervious film of gold to prevent the escape of deuterium. When a vacuum is suddenly created in the chamber in which the device is mounted, rapid out transport of deuterons takes place resulting in the accumulation of deuterons at the junction of Pd and MnO. This sudden entrapment of deuterons results in a big burst of $> 10^6$ neutrons, accompanied by explosive release of gas, biaxial bending of the Pd plate following plastic deformation, besides considerable heat evolution. The temperature is estimated to cross 800 C momentarily due to rapid phase change near the surface bordering MnO. All the phenomena except neutron output are however observed with hydrogen loading also indicating that the heat release is due to non-nuclear causes. These investigators were able to induce a neutron burst from the same Pd sample a few times consecutively by redeuterating the sample again after each burst followed by rapid outgassing (See Fig.15).

Note the similarity of this approach to the "on-off effect" reported by Arata and Zhang / 82/ (Sec.5). While Arata & Zhang have used temperature change to create explosive desorption of D_2, Yamaguchi et al have used a rapid pressure release to attain the same result.

15. *Neutron Emission from a D_2 Gas Discharge Tube with Pd Electrodes*

Wada and Nishizawa of Nagoya University have carried out a simple gas discharge experiment with a pair of Pd electrodes (2 mm dia x35 mm long each) /101/. The electrodes which were mounted on copper stems inside a 300 ml glass bulb (See Fig. 16) were first activated by the application of 12 Kv, 60 Hz AC voltage under vacuum (10^{-5}bar). The bulb was then filled with D_2 gas at 1 bar pressure. The absorption of the gas by the activated Pd was measured by the drop in pressure (See Fig 16a). About 55 hours later when the pressure had attained a steady value the Pd rods were "stimulated" by creating a HV discharge once again. (The time duration for which the HV was applied is not given in their paper.) A large burst of 10^5 - 10^6 neutrons was observed over a period of 63 seconds. This was followed thereafter by several smaller bursts intermittently over the next 50 hr period. Wada et al have attributed the occurrence of these spontaneous neutron bursts to a "breathing" process akin to the on-off effect of Arata & Zhang described earlier. A second HV discharge stimulation at 95 hours from the commencement of the experiment resulted in yet another neutron burst as may be seen in Fig. 16b. Two more such neutron bursts were observed subsequently following HV stimulation but their peak values were weaker. Interestingly the used Pd rods never showed neutron emission again although they did soak up considerable amounts of deuterium following "activation". Similar experiments with H_2 gas did not yield neutrons eventhough the absorption characteristics of H_2 in Pd were noted to be similar.

Y. Kim of Purdue University has recently analysed /102/ this experiment and pointed out that the neutron emission here could be explained on the basis of a conventional beam target process. Measurement of the tritium yield in such experiments may give a clue as to whether or not "cold fusion" is taking place.

16. *First Observation of Neutron Emission from Chemical Reactions*

Arzhannikov et al of the Institute of

Nuclear Physics in Novosibirsk have reported /103/ the generation of neutrons during the reaction of LiD crystals with D_2O /104/ as well as during certain oxidation-reduction reactions of complex deuterized salts of Pd and Pt such as $Pd(ND_3)_2C_3$ and $(ND_4)[PtCl_6]$ with Zn /105/. In the former experiment about 30 g of D_2O was placed in a test tube and LiD crystals 0.3 mm to 4 mm in size were dropped into the test tube one at a time. The reaction of LiD with D_2O being exhothermic the temperature of the test tube increased to about 80 C. Neutron production was observed during this phase as evident from the lower figure in Fig.17, and corresponded to a few tens of neutrons per gram of deuterized matter. It is noteworthy that neutron emission was observed only during reactions with deuterized salts of these metals; no neutrons were detected when the hydrogen version of these salts were used (See upper part of Fig.17). Arzhannikov et al have not attempted to provide any theoretical explanation for the origin of these neutrons.

17. Cluster Impact Fusion

Beuhler et al /106/ of the Brookhaven National Laboratory discovered that nano-ampere beams of singly ionized clusters of D_2O ice crystals carrying energies of 200 to 325 Kev each, corresponding to 10 to 1000 ev per deuteron, when impinged on deuterated targets such as TiD, $ZrD_{1.65}$ and CD_2 produced an anomalously high yield of (d-d) reactions. No reactions were observed either with H_2O clusters impinging on TiD nor with D_2O clusters bombarded on TiH targets. The fusion rate with D_2O on TiD was maximum when the number of D_2O molecules per cluster was about 100, and corresponded to 0.1 reactions /s/d-pair . This implies a discrepancy by a factor of over 10^{10} with respect to expected rates based on known low energy (d-d) reaction cross sections in the incident deuteron energy range of a few hundred ev. This experiment was immediately interpreted by physicists as implying that (d-d) cross sections in the low energy range was perhaps much higher than accepted hitherto. However more detailed analysis of the experiment carried out by Echenique et al /107/, Y.C. Cheng et al /108/ and Rabinowitz et al /109/, modelling the phenomena occurring from the instant the D_2O cluster impacts the target, properly accounting for the enhanced maxwellian tail that results following energy sharing between the target and cluster atoms involved, have brought out the important role of heavy atoms such as O in D_2O and Ti, Zr or C in the target in the dynamical processes occurring immediately following the impact. These computations have however used only the presently accepted (d-d) cross section data. Thus it appears that the phenomenon of cluster impact fusion which has also been labelled as "lukewarom fusion", may have no direct relavance to cold fusion after all, although it has certainly helped bridge the gap between hot and cold fusion /110/.

18. Fracto-fusion

Almost from the beginning of the cold fusion "era", it has been conjectured that the reported neutron emission (See Secs. 4 & 9) could be explained on the basis of what has come to be known as "fracto-fusion", namely (d-d) reactions caused by deuterons accelerated by the high electric field generated between opposite faces of an internal fracture in the deuterated metal matrix /111,112/. It is well known from the exhaustive studies of Dickinson et al /113/ that transient electric fields of more than 15 KV/cm are generated across cleaved surfaces of ionic crystals or fractured insulators. In fact Klyuev et al of USSR carried out an experiment /114/ as early as in 1986 to specifically verify the possibility of neutron emission through such a mechanism by impacting a "striker" of 50 g mass accelerated to a velocity of 200 m/s on an LiD single crystal target. They

detected on an average 10 neutrons/shot in a 75 shot experiment. In the case of hydrides of Pd and Ti also it is well known that large cracks and fissures are formed following a high degree of hydrogen (or deuterium) loading in them. Cohen and Davies /115/ have computed the electric potential that may be expected to be generated when a crack is initiated and "propagates" in PdD_x or TiD_x and show that the observed neutron bursts, particularly in the Frascati type experiments involving the thermal cycling of TiD_x chips in liquid nitrogen, can indeed be explained by such a fracto-fusion mechanism. In fact many experimenters have detected the occurrence of such fractures by means of piezo electric acoustic sensors /116/. But so far no clear cut correlation has been established between acoustic pulses and neutron bursts.

In a beam-target type neutron production process relevant to fracto-fusion however one expects the neutron and tritium yielding branches to have near equal probability and hence the anomalously low ($\sim 10^{-8}$) neutron-to-tritium yield ratio observed in some experiments is inconsistent with the fracto-fusion postulate. Besides it also appears to be difficult to reconcile fracto-fusion with the highly localised production of large amounts of tritium (10^{12} to 10^{14} atoms) in certain site specific hot spots observed in a few TiD_x chips only out of several thousand chips / 93/. In this context it may be of interest to point out that this author and his colleagues have speculated that perhaps the neutron bursts and tritium hot spots may be the result of some sort of cascade reaction or micronuclear explosion /89/. Experiments are currently underway in several laboratories of the world to conclusively establish whether in the TiD_x chips experiments the neutron bursts and tritium hot spots are correlated at all, and also whether the (n/t) yield ratio is unity or really as small as 10^{-8}, and thus settle the question as to whether fracto-fusion or microexplosion or some other mechanism is the root cause of nuclear reactions in these experiments.

19. *Indication of Anomalous Enrichment of Pd^{106} During Electrolysis*

Rolison and 'O' Grady of the Naval Research Laboratory, Washington D.C. reported /117/ some preliminary but startling results at the NSF/EPRI meeting of October '89 /27/ on their probable detection of a change in the isotopic composition of the Pd in the near surface layers of two Pd cathodes electrolysed in D_2O. Their very careful and painstaking mass spectrometric analysis carried out using a sophisticated Time of Flight - Secondary Ion Mass Spectrometer (TOF - SIMS) had indicated that two D_2O electrolysed Pd samples exhibited a greater than 20% enrichment in the intensity of the m/Z = 106 peak with a corresponding decrement in m/Z = 105 intensity, whereas both a control Pd sample as well as one electrolysed in H_2O corresponded only to natural Pd isotopic composition. This result created great excitement among physicists as it implied the possible involvement of Pd nuclei in the anomalous nuclear phenomena associated with cold fusion. Specifically it suggested the possible occurrence of direct neutron transfer reactions between deuterons and Pd^{105} resulting in the formation of Pd^{106}.

At the Salt Lake City cold fusion meeting of March 1990, Rolison et al presented a summary of their further investigations /118/ which indicated the possibility of existence of some experimental artifacts which could have contributed to some errors in their previous conclusions. They found that presence of trace levels of ZrO (Zirconium oxide) species as a surface contaminant in LiOD derived Pd samples could have given rise to an m/Z signal in the same region as that of Pd^{106}. But their Li_2SO_4 derived Pd samples were found to be Zr free. After an involved and very exhaustive experimental campaign and after eliminating or

accounting for all other possible sources of error they concluded /118/ that "a relative enrichment at m/Z of 106 that cannot be attributed to heretofore identified plausible chemical interferents still exists", thereby keeping the door open to the possibility that cold fusion may still encompass nuclear reactions involving Pd and perhaps Li nuclei as well. In particular there has been considerable speculation that the well known reaction between Li^6 and d leading to two alpha particles plus 22.3 MeV of energy may be occurring on the surface of Pd cathodes during the excess heat experiments of Fleischmann et al and some others. But to be fair, all talk of any nuclear reactions occurring in the electrolytic cells involving particles other than deuterons can only be treated as "speculation" for the present.

20. *Remarks on the Poor Reproducibility of Results*

One of the unique features of cold fusion experiments and possibly the main reason for this phenomenon to be looked upon with considerable degree of skepticism /119/ by the scientific community in general is the poor reproducibility of the experimental results. During the crucial months immediately following the first announcement by Fleischman and Pons there was a scramble the world over to replicate the apparently simple "battery and bottle" electrolysis experiment. After weeks and months of patient experimentation however many experienced research groups failed to obtain any positive evidence for the claimed phenomena. They neither found excess heat nor neutrons, tritium or gamma rays /120-134/. Some experiments that were tailored to look for charged particles also failed to give any positive results /123,134/. By December 1989 there were perhaps more experimental papers with "negative results" published on the topic of cold fusion than those with "positive results". However as of the present writing the situation has fully reversed, following the appearance of a large number of papers with positive results during 1990 as described already. The persistent efforts of many dedicated experimentalists appears to have turned the trend and the reproducibility has begun to improve significantly, as may be seen for example from the title of one of the recent papers from Los Alamos namely, "Reproducible Neutron Emission Measurements From Ti Metal in Pressurised D_2 Gas"/135/.

21. *Summary of Experimental Findings*

In the two year period since the appearance of the first reports of cold fusion, it is obvious that the authenticity of the phenomenon, namely occurrence of "anomalous nuclear reactions in solid-deuterium systems" has been established beyond doubt, although admittedly the phenomenon is still "sporadic" in nature and not yet reproducible at will. The main findings of the cold fusion experiments todate may be summarised as follows:.

(i) The production of excess heat in D_2O electrolysis with Pd (or Ti) electrodes has been fully confirmed. The steady state or baseline excess heat is found to increase with current density and is typically not more than about 30% of the input joule heat in the case of D_2O electrolysis with Pd cathodes. The maximum excess power observed so far is $\sim 100 W/cm^3$ of Pd. (This translates to $\sim 10^{14}$ fusion reactions / s/cm^3 or $\sim 10^{-9}$ fusions/s/d-pair). The integrated energy yield has been over 50 MJ/cm^3. However during the sporadic heat bursts (observed only by a few groups so far) peak power levels have been 20 to 30 times the input power. In molten salt electrolysis with Pd anodes the excess power has been as high as 15 times the input electrolytic power for more than a day at a specific power of 0.6 Kw/cm^3.

(ii) He^4 has been detected by mass spectromet-

ric analysis in the electrolytic gases of Miles experiment /55,58/ as well as in the 0.5 g Pd button which generated 5 MJ of energy in the molten salt experiment. While the quantum of He^4 measured in the gas stream was substantial that in the Pd button was still much below that expected from the magnitude of the integrated excess heat. These results point to the generation of He^4 on the surface of Pd rather in the bulk matrix.

(iii) Neutrons have been measured both in electrolysis and gas loaded targets. They appear at a very low (10^{-20} to 10^{-23} neutrons/s/d-pair) steady state level ("Jones level") a few sigma above background count rates or in the form of bursts lasting from microseconds to minutes to even hours at times. Neutron multiplicity and statistical analysis measurements indicate that neutron emission has both a singles component following Poisson distribution (one neutron emitted at a time) as well as bunches of several hundred neutrons /79,80,136/. Several groups have measured the neutron energy to be 2.45 MeV. However atleast two groups have reported observing an additional 4 to 6 MeV component. Surprisingly no group has detected any 14 MeV neutrons so far.

(iv) The production of tritium both in electrolytic and gas loading experiments stands confirmed. The suspicion that tritium seen in cold fusion experiments is due to prior contamination of Pd has been ruled out by the fact that in several experiments neutrons and tritium were generated "concomitantly".

(v) The neutron-to-tritium yield ratio appears to be very small; it is mostly $\sim 10^{-8}$ although in some cases values as "large" as 10^{-3} have been reported.

(vi) Charged particles with energies varying from < 1 MeV upto several MeV have been observed in many experiments. One group has reported measuring monochromatic tritons of 5 MeV energy from deuterium gas loaded titanium samples. (It may appear to be difficult to reconcile this last observation with the non-observation of 14 MeV neutrons by any group so far, but it must be appreciated that the 14 MeV neutron production rate in Cecil's experiments for example would have been hardly 1 neutron per hour as it would be only 10^{-5} times the triton generation rate; It is impossible to detect such a low neutron production rate in experiments.)

(vii) Soft X-rays have been detected from Pd in a D_2O electrolysis experiment through radiographic imaging of the cathode.

(viii) Acoustic signals have been measured both in Pd-electrolysis experiments as well as Ti gas loaded targets.

(ix) Electromagnetic signals (radio emission) have been picked up in electrolytic experiments using a Rogowsky coil.

This plethora of experimental evidence obtained using a veriety of experimental techniques points to the occurrence of many different nuclear reactions, induced by deuterons.

For the benefit of potential new entrants to the field of cold fusion who wish to try their "luck" in carrying out similar investigations this reviewer has summarised in the Appendix the various steps involved in conducting such experiments as he perceives it.

22. *"Puzzles" of the Cold Fusion Phenomenon*

The experimental findings listed above can be condensed in the form of a series of "puzzles" that any theoretical model which seeks to explain cold fusion phenomena should account for.

a) The first puzzle is the very occurrence of nuclear reactions in a solid atomic lattice at near-ambient temperatures. It is believed that the free electrons and deuterons in the metal lattice play a crucial role in screening and lowering the coulomb barrier and help increase tunnelling probability.

b) The second important puzzle is the several orders of magnitude mismatch between experimentally observed excess power/heat and neutron or tritium yields. This clearly indicates that excess heat in electrolysis is definitely not due to simple (d-d) reactions which would have given rise to copious levels of neutron or tritium production. It was recognised right from the inception that "excess power levels in the watt range for example, would imply production of more than 10^{12}n/s and this would have resulted in lethal levels of radiation doses to the experimenter. Hence excess heat, if indeed of nuclear origin, has to be due to some other nuclear reaction in which the product is a non-radioactive charged particle. For example a 2 body (d-d) reaction leading to He^4 has been postulated as the most probable candidate for this, although a (Li^6 + d) reaction leading to two He^4 nuclei is also a possibility. Two recent experiments /58,60/ have provided the first "confirmation" that He^4 is indeed being produced in electrolytic cells wherein excess heat is measured.

c) The third puzzle needing explanation is the experimentally observed correlation between current density and excess power both in D_2O electrolysis and molten salt electrolysis. In other words the precise role or influence of the "electrochemical compression process" (or the so called fugacity) on the fusion reaction rate needs to be understood. A "sub puzzle" in this context is the reason for the inordinate delay between commencement of electrolysis and commencement of excess heat which needs justification. Among the various models put forward to address this question, the Transmission Resonance Model (TRM) of Bush /137/ appears to be the most successful so far.

d) The fourth puzzle is the fact that no tell tale high energy X-rays which would give a signature of energetic charged particle generation has been measured so far although very soft X-rays which cannot escape from the cell but barely escape the Pd cathode have been indirectly detected through fogging of X-ray film / 58,86/. This could imply that no high energy fusion products are released during these nuclear reactions. The common explanation offered for this is the postulate that the energy released in the nuclear reaction is somehow directly absorbed by the lattice (as phonons) / 138/ or electromagnetically transferred to the electrons akin to an internal conversion process. Walling and Simons /139/ have attributed this to "radiationless relaxation (RR)" of the transient excited He^4.

e) Although the excess heat phenomenon is obviously not due to simple (d-d) reactions, the very fact that ~ 2.45 Mev neutrons have been measured in a variety of experiments, indicates (d-d) reactions do nevertheless occur in deuterated Pd and Ti samples. But the puzzling part here is why is the (n/t) ratio not unity? This "branching ratio anomaly" may be characterised as the 5th puzzle of cold fusion. Some theorists have invoked a Phillips-Oppenheimer type process for explaining this /139,140/.

f) The sixth puzzle is the apparent non-generation of 14 MeV neutrons. So far nobody has detected any 14 Mev neutrons in cold fusion experiments. The tritium generated in (d-d) reactions is expected as per present day "vacuum nuclear physics" concepts, to have about 1 Mev of energy, in which case it should have produced 14 MeV neutrons with a probability of 10^{-5} during the slowing down of the suprathermal tritons in palladium deuteride. This puzzle

has so far been explained by invoking the postulate that excess energy is carried away directly by the metal lattice as discussed in (d) above.

g) The 7th puzzle is the recently measured 4-6 Mev neutron component which according to A. Takahashi /83/ suggests the occurrence of 3 body 3D reactions. He has proposed that the 15.9 Mev deuterons generated in 3D fusion gives rise to 4 to 6 MeV neutrons during its slowing down in PdD_x. The puzzle then is how come in 3D reactions energetic charged particles are generated but not in 2D reactions?

h) The 8th puzzle, if it may be called so, is the possible occurrence of nuclear reactions involving host metal nuclei such as the Pd nuclides or the Li isotopes deposited on the cathode surface during electrolysis. This possibility arises from the inconclusive but highly suggestive and speculative Pd isotopic analysis results of Rolison et al /117/ discussed in Sec.19.

i) The 9th and last puzzle is the poor reproducibility of the results be it in electrolytic experiments or gas loading experiments or other techniques, strongly suggesting that all the experimentalists are missing an important and key "element" which is crucial to achieving "success". The question is : Is it a metallurgical factor, or a chemical impurity or a nuclear trigger or some other physical parameter that is responsible for the poor reproducibility. That is a puzzle yet to be solved.

The above list of puzzles clearly indicate that the cold fusion phenomenon is in the words of Hegelstein /138/ "....in direct contradiction to very basic precepts of nuclear physics..... it seems that an extremely fundamental and totally unexpected change in our understanding of physics would be required to even begin accounting for the various "miracles" that have been claimed. Indeed this was also reflected in the conclusions of the final report of the US DOE's Cold Fusion Panel /16/ quoted in the Introduction to the present paper.

23. *Approaches to a Theoretical Understanding of Cold Nuclear Fusion*

A number of theoretical attempts /137-171/ have been made during the last couple of years to explain some or all of the above "puzzles". Broadly speaking there appear to be three basic issues that any theory of cold fusion must address. These are : (i) How exactly does the host metal lattice help in increasing the fusion rate inspite of the deuteron energy being apparently small (A deuteron in thermal equilibrium for example would have only a few tens of milli-electron volts of energy.) (ii) What are the mechanisms, if any, by which the energy released in the nuclear reaction can be directly transferred to the host meta lattice? and (iii) The more general but fundemental issue of what Preparata calls /141/ the problem of "asymptotic freedom", namely how does it happen that lattice interactions with their typical time scales of 10^{-16} sec^{-1} and distances of 10^{-8}cm "tamper" with nuclear forces with typical times of 10^{-21} sec^{-1} and distances of 10^{-12} cm?

Majority of the theoretical studies have addressed the first of these issues namely the possible methods of enhancement of fusion reaction probability (p_r) from a negligible value of about $10^{-70}sec^{-1}$ for a D_2 molecule in free space /142/ to levels in the range of 10^{-9} to $10^{-23}sec^{-1}$ experimentally observed in the solid environment. Traditionally the fusion reaction probability p_r is expressed as the product of two factors : The first factor is the barrier penetration probability which pertains entirely to the electrical forces of repulsion. The second factor is the intrinsic nuclear reaction rate which refers entirely to the nuclear forces. Thus p_r is expressed as follows:

$$p_r = [e^{-G}] . A$$

For example for the (d-d) reaction, factor A is given by $[3x10^{-13}.E_d^{-1/2}]$ when E_d is in ev and p_r is in sec^{-1}. The first factor namely (e^{-G}) represents the barrier penetration probability and is dependent crucially on the modified Gamow tunnelling parameter, G. Clearly the magnitude of G is significantly decreased in a solid environment due to charge screening and other effects leading to an enormous enhancement of the tunnelling probability.

In order to account for the fusion reaction rates which seem to be occuring in cold fusion experiments, the value of parameter G has to decrease from about 175 applicable to D_2 molecules in free space to about 80 (for Jones level reaction rate) or -70 (for Fleischmann-Pons heat rates). The physical phenomena which have been considered as contributing factors for decreasing G are: (a) Conduction electron screening (b) Deuteron screening (c) Heavy electron concept (d) Role of effective deuteron mass (e) Effect of velocity distribution of the deuterons and (f) Deuteron channelling effects.

Interestingly writing under the title "Cold Fusion Prospects" /143/, Rand McNally Jr had discussed the theoretical possibility of achieving a reduced coulomb barrier in solid media even as early as in 1983. Parmenter et al /144/ have computed the tunnelling probability on a simple model considering the interacting particles to be composite particles comprising a bare deuteron plus an associated screening cloud of electrons. They have adopted a Modified - Thomas - Fermi - Mott equation methodology and derived p_r values in the range of 10^{-25} to 10^{-23} sec^{-1}. Vaidya and Mayya /145/ account for the combined screening effect of electrons and deuterons using a "Jellium model" to obtain values in the range of $10^{-36}sec^{-1}$ at 700 K to $10^{-14}sec^{-1}$ at 50 K. Rabinowitz /146/ finds that use of an effective deuteron mass of only 0.1 times the free deuteron mass is adequate to give fusion rates in the experimental range.

References 147 to 156 discuss various screening and other mechanisms proposed to enhance tunnelling probability. However Leggatt and Baym /157/ have argued that if the effective repulsion of two deuterons is substantially weakened by solid state effects then these effects should also lead to a greatly increased binding energy of alpha particles to the metal which clearly is not borne out by experimental observations. Thus working within the framework of the lowest order Born-Oppenheimer approximation they have carried out a rigorous computation of the many body screening effects in Pd under equilibrium conditions and conclude that coulomb barrier penetration cannot be enhanced anywhere near the rates required to match the experiments. They thus imply that non-equilibrium conditions may be important.

Dasannacharya and Rao /158/ have pointed out that in a system with large anharmonicity such as Palladium deuteride there could be short lived large energy fluctuations of a small number of particles resulting in large momentum transfers, 10^2 to 10^3 times $(mKT)^{1/2}$. This could result in a few deuterons acquiring energies as high as 50 ev, enabling thereby high fusion rates. Kim et al /159/ and Rice et al /160/ have shown how the deuteron velocity distribution especially an enhanced maxwellian tail can significantly influence fusion rates in the presence of electron screening effects also. Using an essentially classical model Gryzinskii /161/ has propounded a quasi-molecular mechanism of coulomb barrier tunnelling. His theory hinges on the postulated presence in the PdD lattice of a high concentration of relatively long lived, compact quasi-molecular ions namely D_2^+, which radiatively collapse to cause fusion. Tabet and Tenenbanum /162/ look upon cold fusion as resulting from a lattice collapse leading to "deuteron drag" following thermodynamic instability. Lali Chatterjee /163/ has considered the influence of the kinetic energy available to the final nuclear particles in the (d-d) reaction

on the neutron- to-tritium branching ratio. Hora et al /164/ have applied a surface double layer model of metals with a "swimming electron layer" of about 0.1 nm thickness on the crystal surface and computed fusion rates. They have accordingly predicted the possibility of achieving power densities in the range of Kw/ cm^3 using multilayered samples.

Bush /137/ has propounded a novel Transmission Resonance Model (TRM) treating the diffusion of deuterons in a solid lattice as a wave mechanics problem. Building upon an idea first outlined by Turner /165/ Bush has shown that a 100 % transmission condition would be satisfied when "an odd integral multiple of the average quarter - wavelengths of the deBroglie waves of the deuterons matches the potential well widths of the particles situated in the PdD_x lattice". He then postulates that when the resonance (or high transmittivity) condition is satisfied the diffusing deuterons get close enough to the stationary particles in the host lattice which form the potential wells (either d or Pd or Li), to have a high probability of undergoing nuclear reactions. Eventhough Preparata /141/ has criticised Bush's model for not clearly spelling out how exactly the barrier penetration probability improves when the resonance condition is satisfied, the TRM model nevertheless seems to be remarkably successful in fitting the highly nonlinear structure of a wide base of experimental calorimetric data. Fig.18 reproduced from Ref./137/ illustrates the ability of his model to explain the excess power results of one of their own experiments.

Preparata /141/ has recently carried out a critical analysis of some of the more important theoretical papers and arrives at the conclusion that in the ultimate analysis one must invoke collective processes wherein the elementary components of condensed matter, namely nuclei and electrons, act in a coherent fashion. Bressani et al /167/ have shown how the barrier penetration problem can be tackled by considering the important role played by the coherent interactions with the quantized electromagnatic field. They have applied the "Quantum Field Theory of Superradiance" formulated by Preparata /168/, to the cold fusion problems.

Julian Schwinger (Nobel Laurate) /169/ has pointed out that the conventional two factor approach applicable under hot fusion conditions namely of seperating overall nuclear reaction rate as a barrier penetration probability followed by an intrinsic nuclear reaction probability, may not be relevant and meaningful for understanding very low energy nuclear reactions in the solid state. He has argued that it is not proper to totally isolate the effect of the electric forces from that of nuclear forces and has advocated dispensing with the "collision dominated mentality of hot fusioneers" to understand cold fusion phenomena. He has formulated a "coherent screening mechanism" provided by the vibrations of the lattice deuterons and successfully derived Fleischmann - Pons excess power levels.

Hegelstein of MIT has independently developed a detailed formulation of a Coherent Fusion Theory /138/. His novel approach is based on a two step reaction mechanism in which incoherent electron capture by deuterons first generates "virtual neutrons" accompanied by coherent neutrino emission ; these "virtual neutrons" are then captured either by deuterons or Pd or even Li to generate tritium or heat. He refers to the latter step as "virtual fusion reaction". The basic premise of his extensive work is that off resonant coupling between two fusing nucleons and a macroscopic system can occur through electromagnetic interactions. His detailed theoretical work shows how neutrino emission can occur coherently and also how the energy released in the "virtual fusion reaction" can be transferred directly to the lattice modes as phonons.

(Hagelstein is widely known for his very original contributions to the theory of X-ray lasers).

One of the intriguing conclusions to emerge from the computational results of several independent theoretical models is that under the conditions pertinent to cold fusion experiments, the probability of (p-d) reactions is surprisingly higher than that of (d-d) reactions /138,161/. In other words it is theorized that the small H_2O component of D_2O is playing an important role in cold fusion phenomenology and hence, it has been suggested, that a systematic study of various effects as a function of the magnitude of the H_2O fraction in D_2O should be carried out.

In summary it may be stated that it is becoming increasingly apparent why and how the physics of nuclear "fusion" reactions in cold condensed matter can be very different from that under hot plasma conditions. In fact already the new phrase "solid state nuclear physics" as distinct from "vacuum nuclear physics" is beginning to be applied when discussing cold fusion phenomena.

24. Concluding Remarks

This reviewer undertook the laborious task of compiling and assembling in a single place a summary of all the experimental results obtained so far in the area of cold fusion when he found that a majority of scientists, particularly physicists, held the view that the phenomenon popularly referred to cold fusion was a "myth" and an "illusion"; one physicist /172/ has even consigned cold fusion to the realms of Langmuir's "pathological science"! However this reviewer has found that many physicists who are staunch "non-believers" are simply not aware of the many excellent experimental results that have been accumulated during the past one year. When confronted with the mounting experimental evidence most skeptics were willing to concede that may be "something interesting was going on after all" in deuterated solids. The purpose of this review is mainly to draw the attention of the Indian scientific community to the recent developments in cold fusion.

While physicists find it easy to accept that (d-d) reactions at the "Jones level" (10^{-20} to 10^{-23}/s/d-pair) can possibly occur in deuterated solids, there seems to be still considerable reluctance on their part to accept the idea that the "excess heat" generation in electrolytic cells could indeed be of nuclear origin. So far the main justification for the nuclear origin of "excess heat" had been the argument that the magnitudes of both excess power (W/cm^3) and excess energy (MJ/mole) involved are such that it is orders of magnitude more than what can be explained on the basis of known chemical phenomenona (reaction enthalpies, phase change effects, stored energy release etc). However the recent observation of significant quantities of He^4 in the off gas stream of electrolytic cells generating "excess power, besides a marginal excess of He^4 in one electrolysed Pd button should perhaps begin to convince the scientific community that proof of excess heat being of nuclear origin is now on hand. However this information is not yet widely known.

In the judgement of this reviewer the infant field of "cold fusion" is rapidly acquiring the status of a respectable new branch of science, and the mysteries behind what this author and a growing number of "converts" firmly believe is one of the most fascinating scientific breakthroughs of our times is slowly being unravelled /173,174/. Indeed the humble "battery and bottle" experiment may well have unexpectedly opened the door to uncharted new realms of physics and nuclear technology.

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ABBREVIATIONS USED FOR CONFERENCE PROCEEDINGS

1) WCFP, Santa Fe, 1989

Workshop on Cold Fusion Phenomena held at Santa Fe, New Mexico, May 23-25, 1989 (This has been published in J. Fusion Energy 9 (1990), Nos. 2, 3 & 4)

2) ICENES-V, Karlsruhe, 1989

Vth International Conference on Emerging Nuclear Energy Systems held at Karlsruhe during July 4-7, 1989 (World Scientific, Singapore)

3) CUCFP, Varenna, 1989

Conference on Understanding Cold Fusion Phenomenon held at Varenna, Italy, during September 15-16, 1989

4) NSF/EPRI Workshop 1989

National Science Foundation/Electric Power Research Institute Workshop on Anomalous effects in Deuterium Metals, Washington DC, October 16-18, 1989 (Published by EPRI, Palo Alto, California)

5) ACCF I, Salt Lake City, 1990

First Annual Conference on Cold Fusion held at Salt Lake City, Utah, March 28-31, 1990 (Published by National Cold Fusion Institute, Utah)

6) SCF, Honolulu 1990

Symposium on Cold Fusion organised during the 8th World Hydrogen Energy Conference held in Honolulu, Hawaii, July 1990

7) ICANEDSS, Provo, 1990

International Conference on Anomalous Nuclear Effects in Deuterated Solid Systems held at Provo, Utah during October 22-25, 1990 (Published by American Institute of Physics)

APPENDIX

STEPS IN A TYPICAL COLD FUSION EXPERIMENT

(1) Choice of host metal/alloy

(Pd, Ti, Zr, Mg, V, Nb-Ti, any hydrogen storing alloy; even a high temperature super conductor (HTSC)!)

(2) Preparation of Samples

(Degassing, surface cleaning, annealing)

(3) Loading of deuterium

(Electrolysis, Gas, Plasma, Ion implantation etc)

(4) Measurement of degree of loading (or deuterium-to-metal atom ratio)

(Weighing, volume increase, resistivity, X-ray diffraction etc)

(5) Stimulation/triggering of fusion reactions (to create non-equilibrium conditions) (Current pulsing, thermal cycling, electrical discharge, application of intense magnetic field, pressure changes, shock wave, projectile impact etc)

(6) On-line diagnostics

(Heat, neutrons, charged particles, X or gamma rays, acoustic or radio emissions)

(7) Off-line (or post experiment) analysis : (He^4, tritium activity, activation products)

(8) Theoretical interpretation/modelling/ analysis.

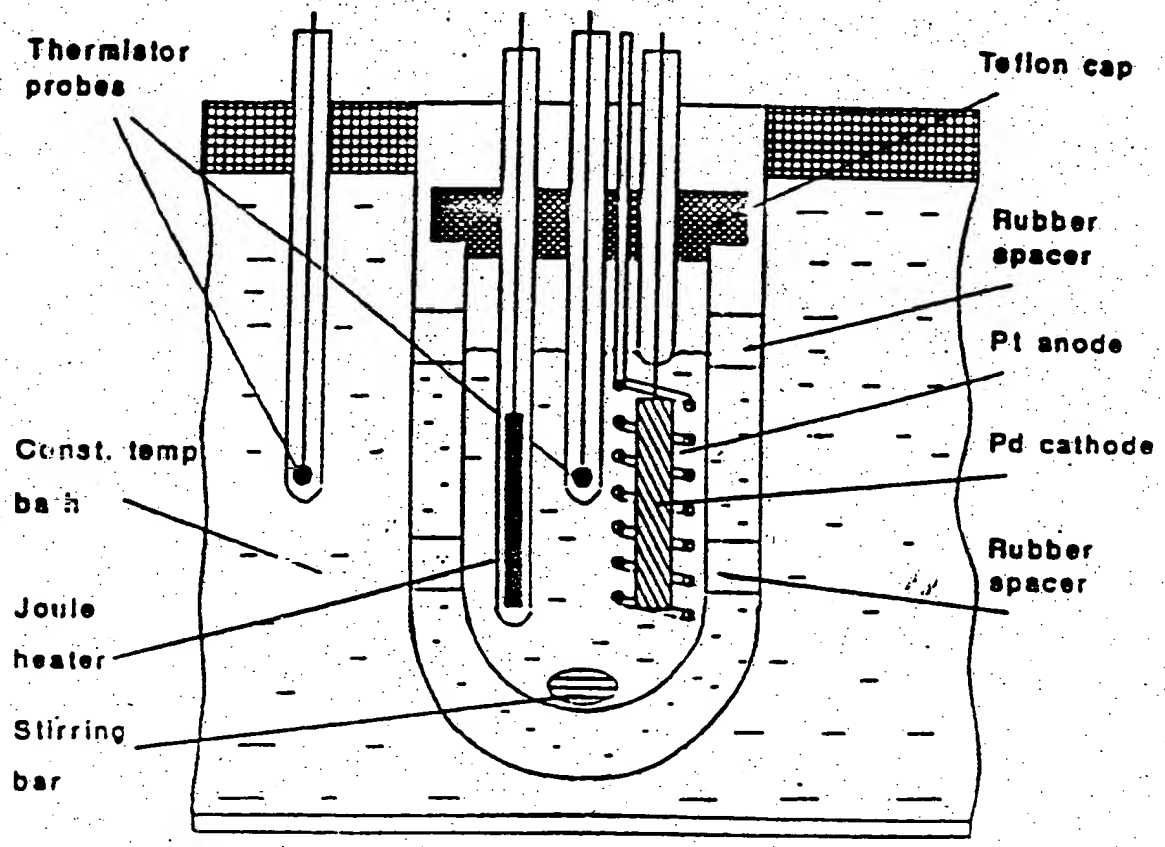


Fig.1 Dewar type electrolytic cell used for excess heat measurements (From Bockris et al /37/)

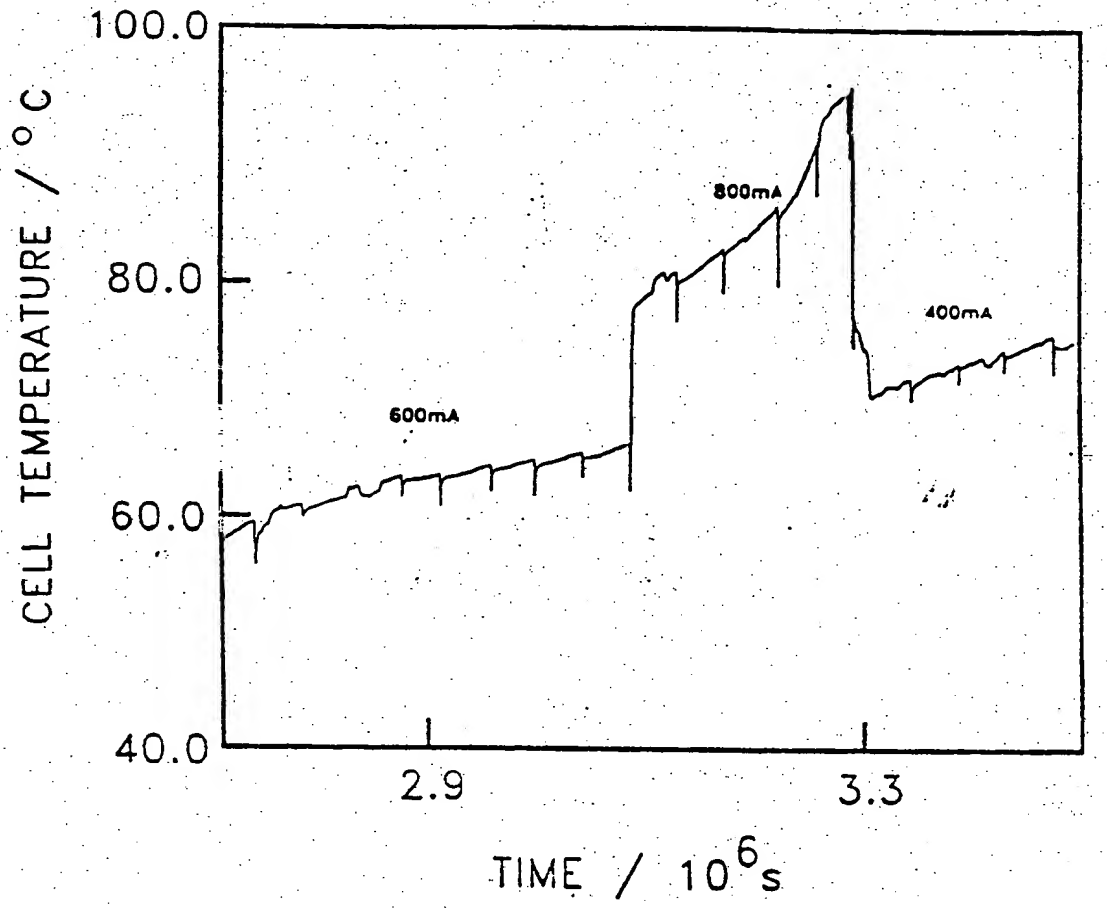


Fig.2 Heat burst event lasting several days during which electrolyte temperature approached boiling point (From Fleishmann et al /45/)

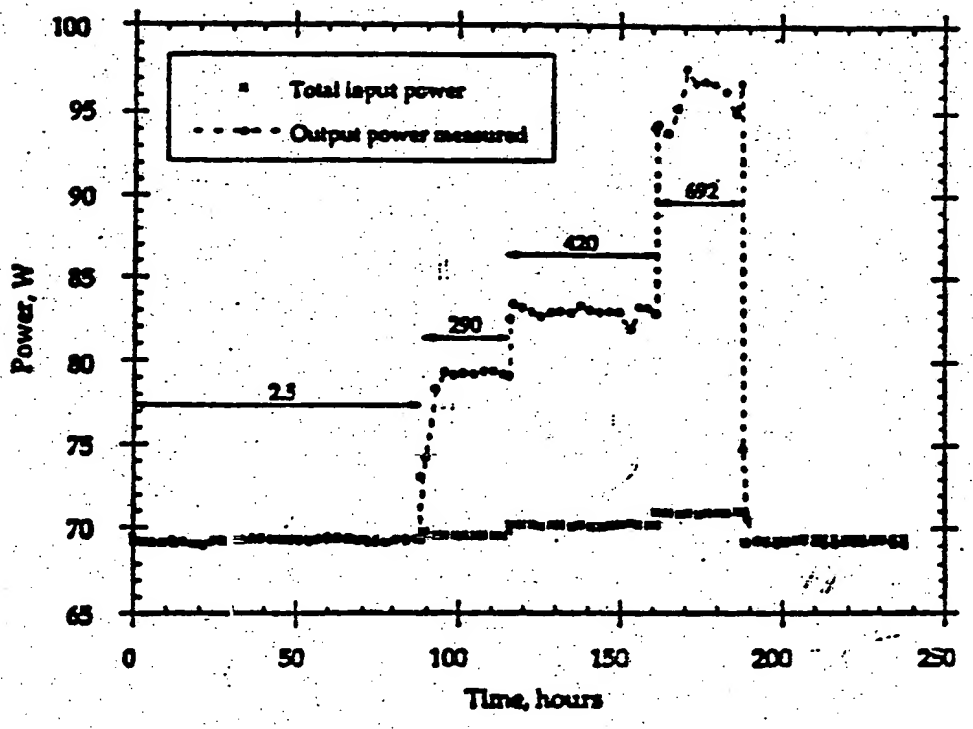


Fig.3 Excess power generating during Molten Salt Electrolysis experiment with Pd anode (From Liaw et al /59/)

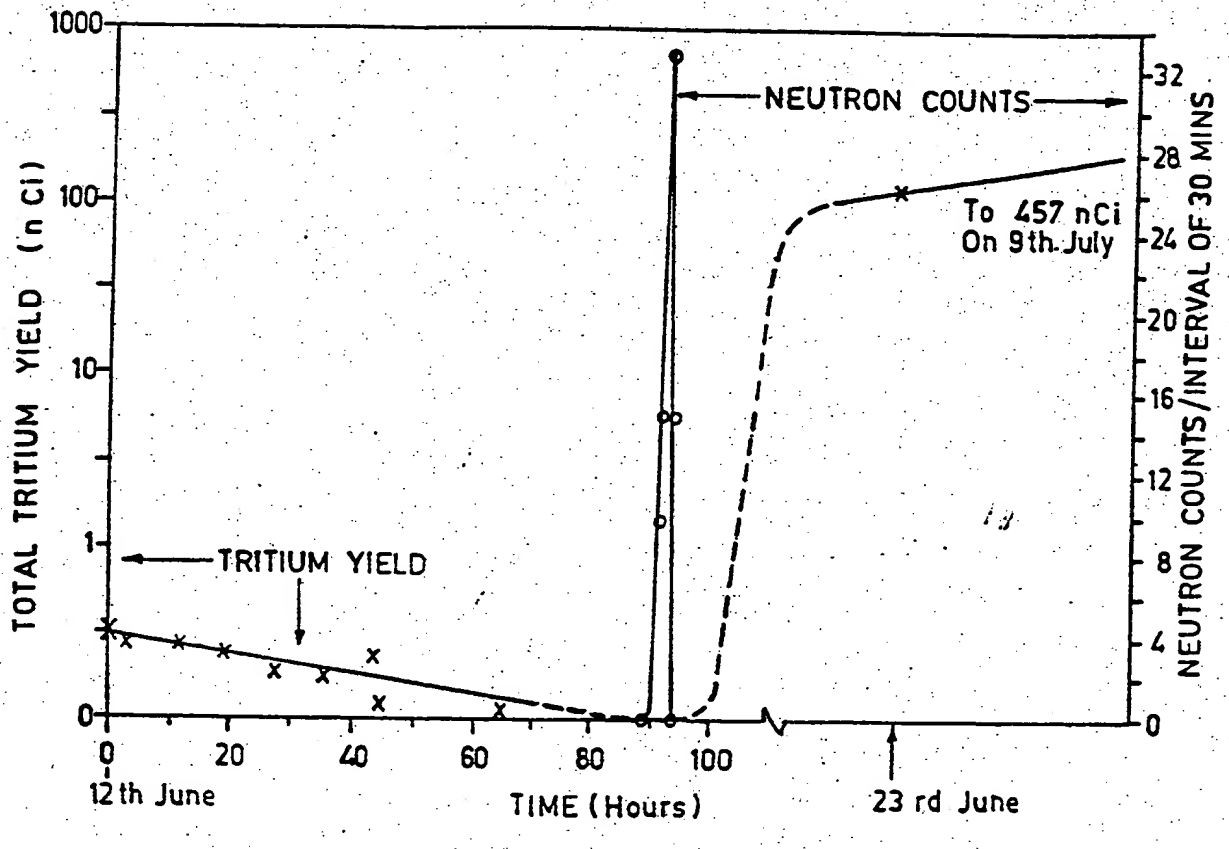


Fig.4 Concomitant generation of neutrons and tritium by a Milton Roy electrolytic cell (From Iyengar et al /62/)

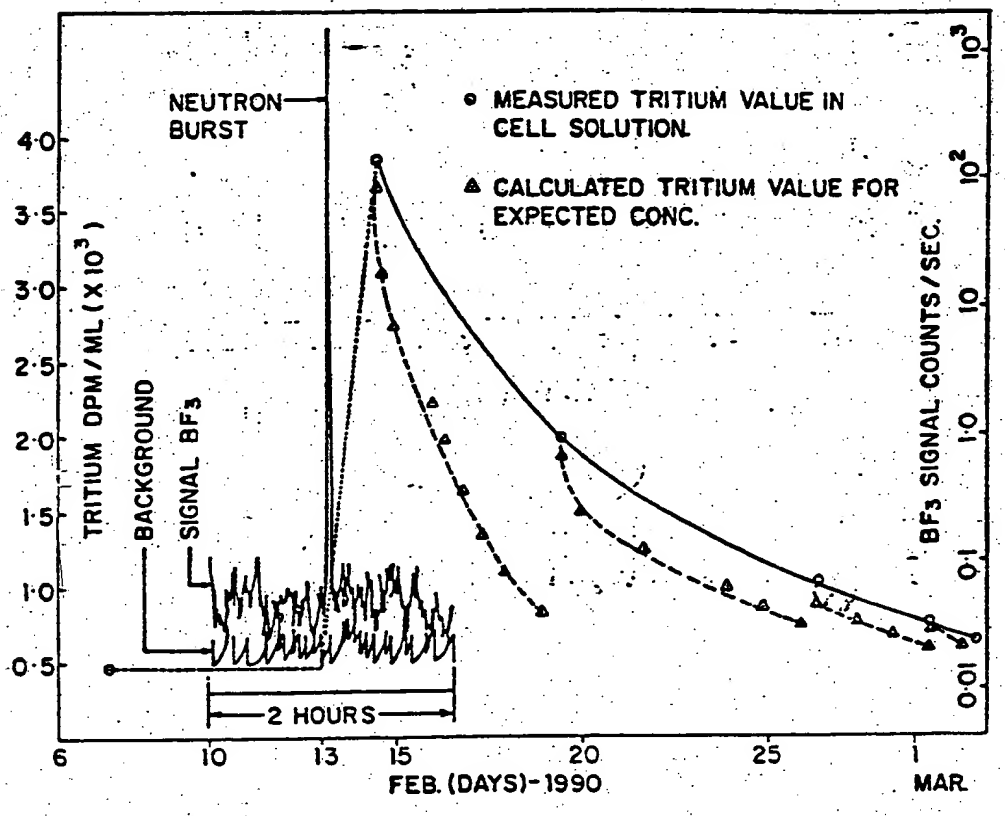


Fig.5 Observation of increased tritium activity following a neutron burst during an electrolysis experiment (From Iyengar et al /62/)

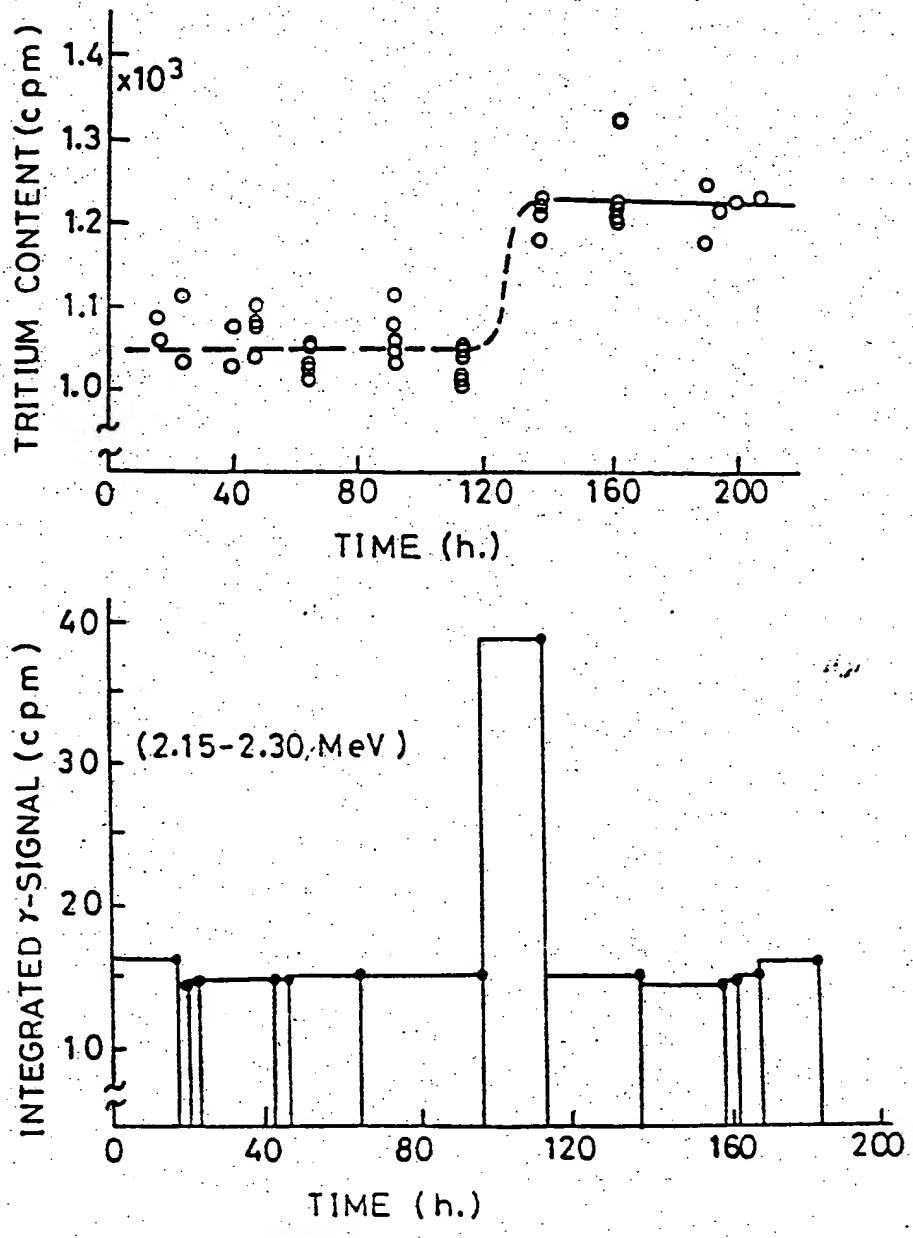


Fig.6 Another example of simultaneous production of tritium and neutrons in D_2O electrolysis (From Sanchez et al/20/)

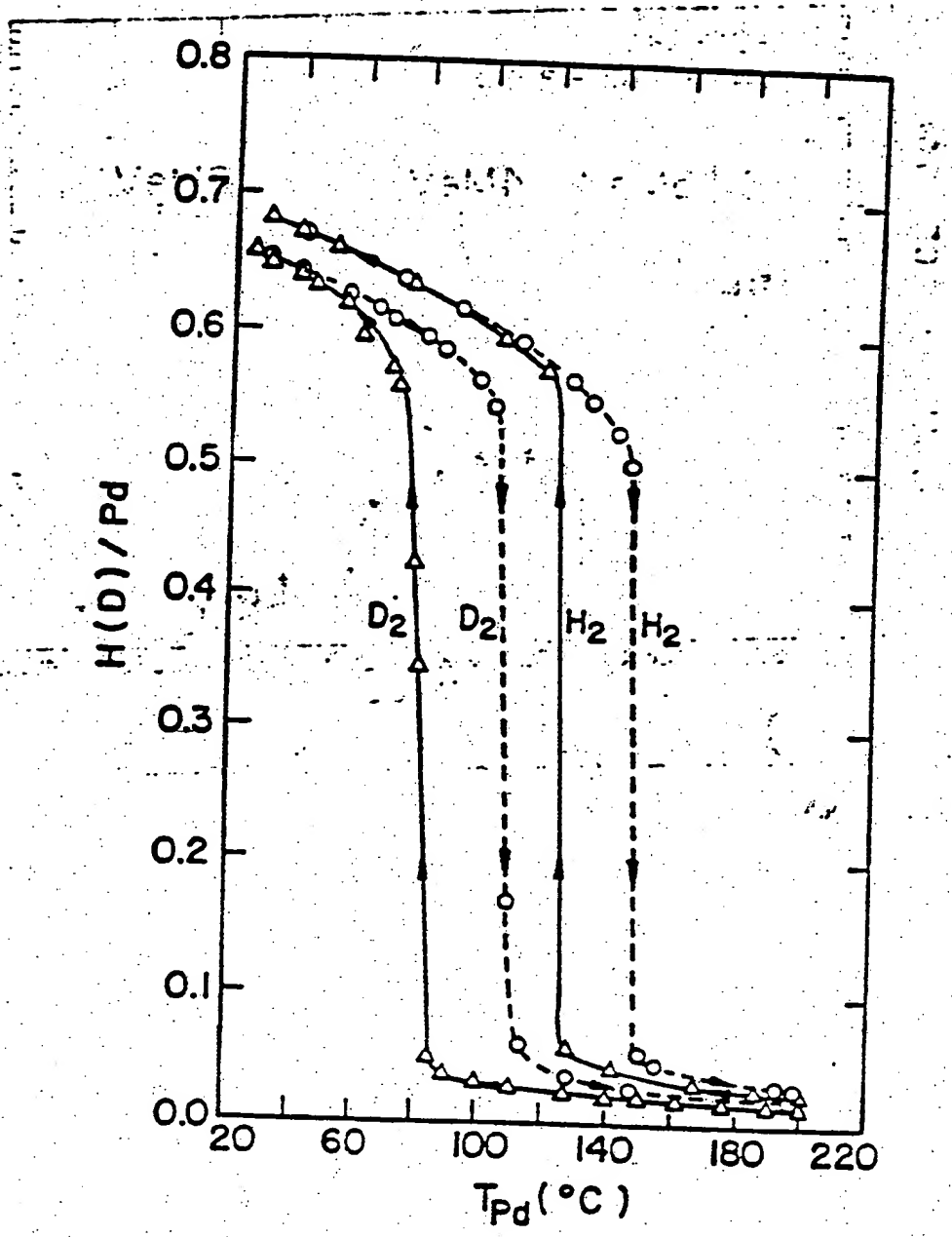


Fig.7 Hysterisis effect in the solubility of H & D in Pd (From Arata and Zhang /82/) (Originally from F.A.Lewis' book)

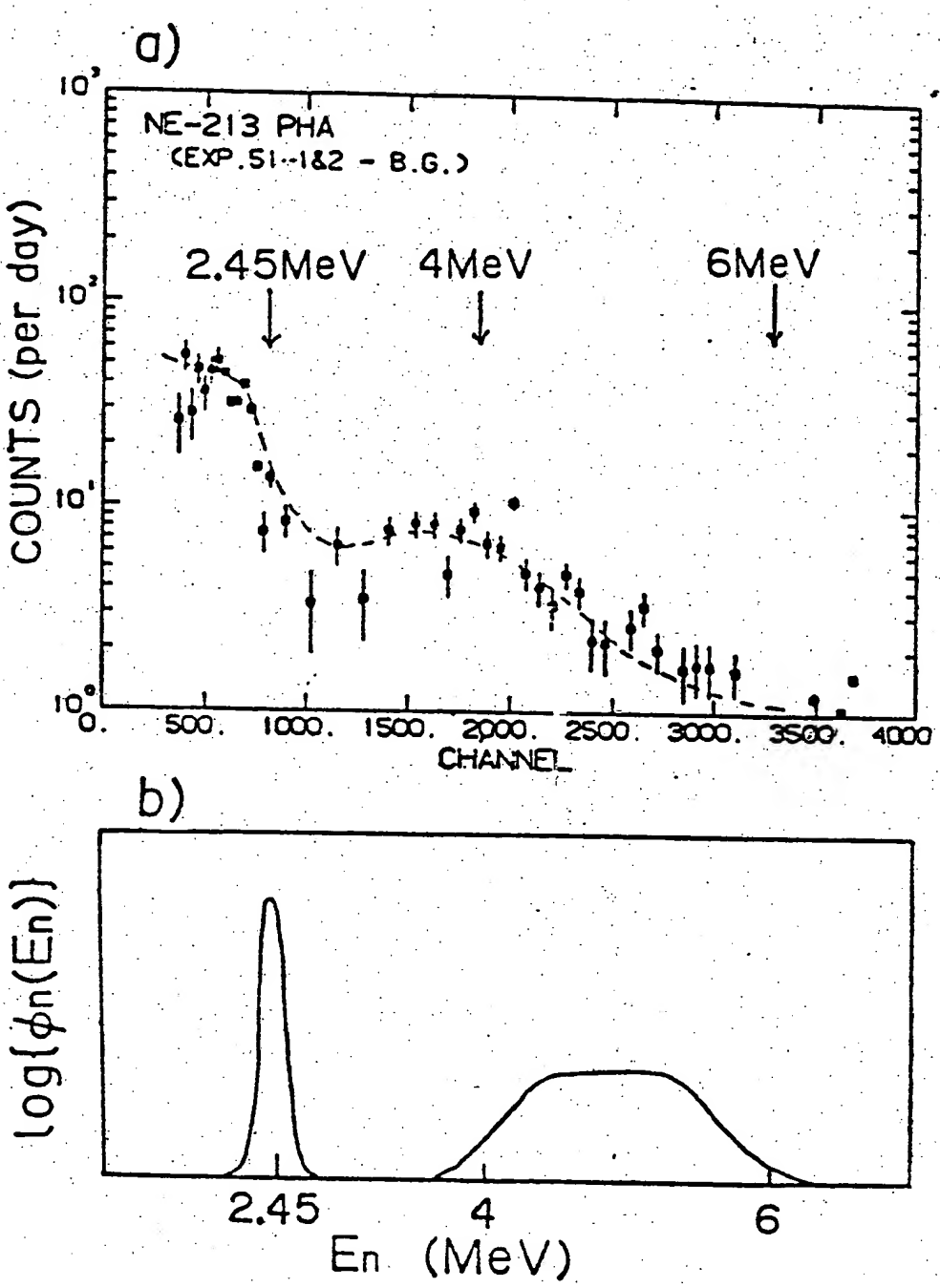
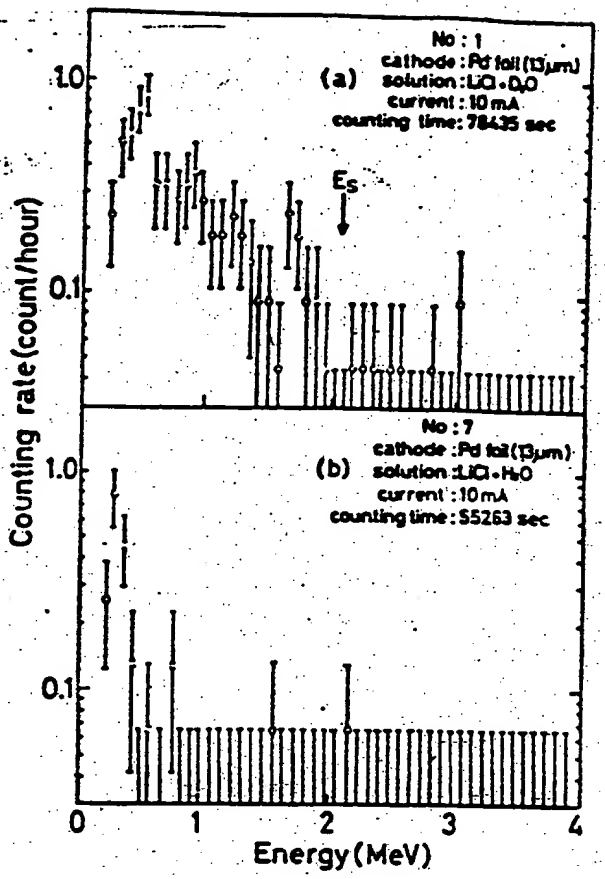
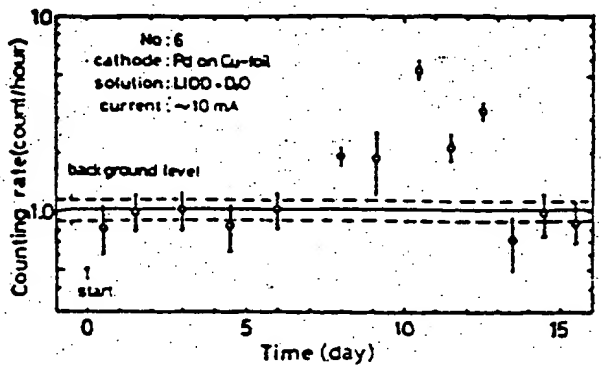


Fig.8 Evidence for 4 to 6 MeV energy neutron component besides 2.45 MeV peak in D_2O electrolysis (From Takahashi et al /83/)

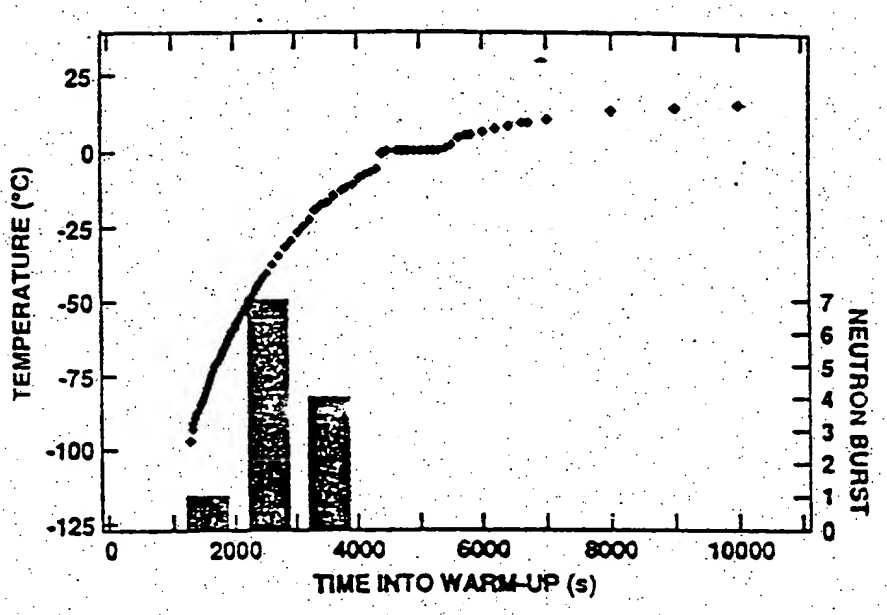


Energy spectra measured with (a) D_2O-electrolytic solution and (b) H_2O-electrolytic solution.



Time dependence of counting rate for the run with a palladium layer on a copper foil, a gold anode, and LiOD solution.

Fig.9 Detection of charged particles from thin Pd Cathode during D_2O electrolysis (From Taniguchi et al /85/)



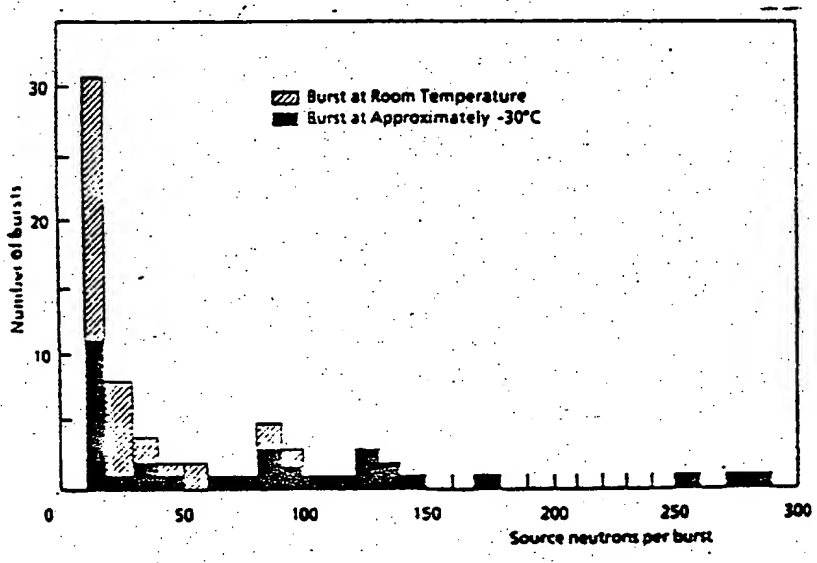


Fig.10 Characteristics of neutron burst production from TiD_x chips subject to thermal cycling (From Menlove et al /17/)

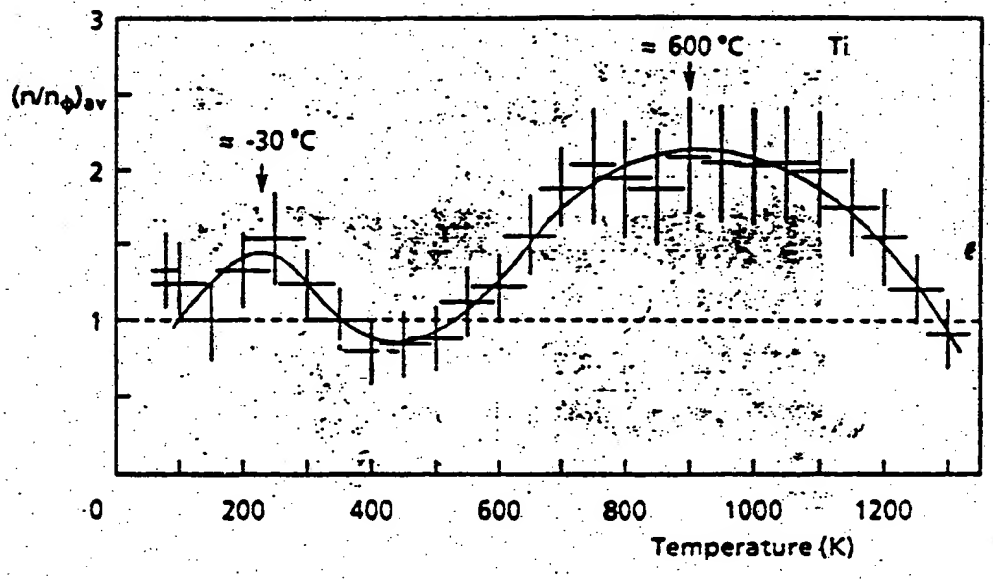


Fig.11 Neutron count rate variation during heating of a deuterated Ti foil (From Zelenski et al /92/)

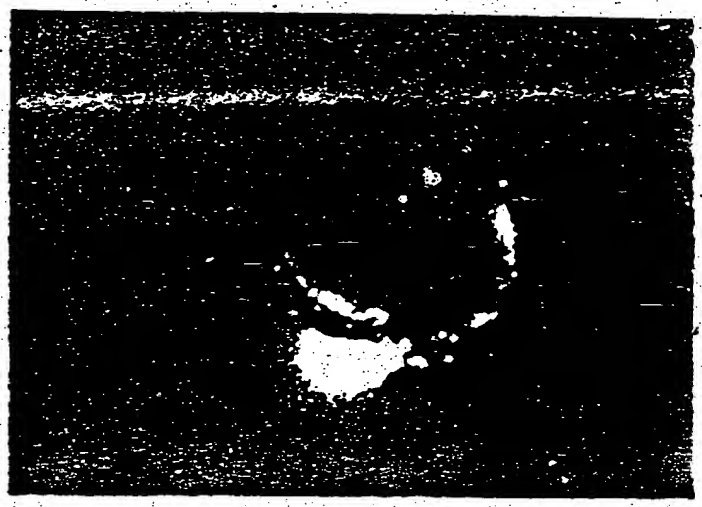


Fig. 12 Autoradiograph of a deuterated Ti chip showing tritium containing hot spots (From Kaushik et al /93/)

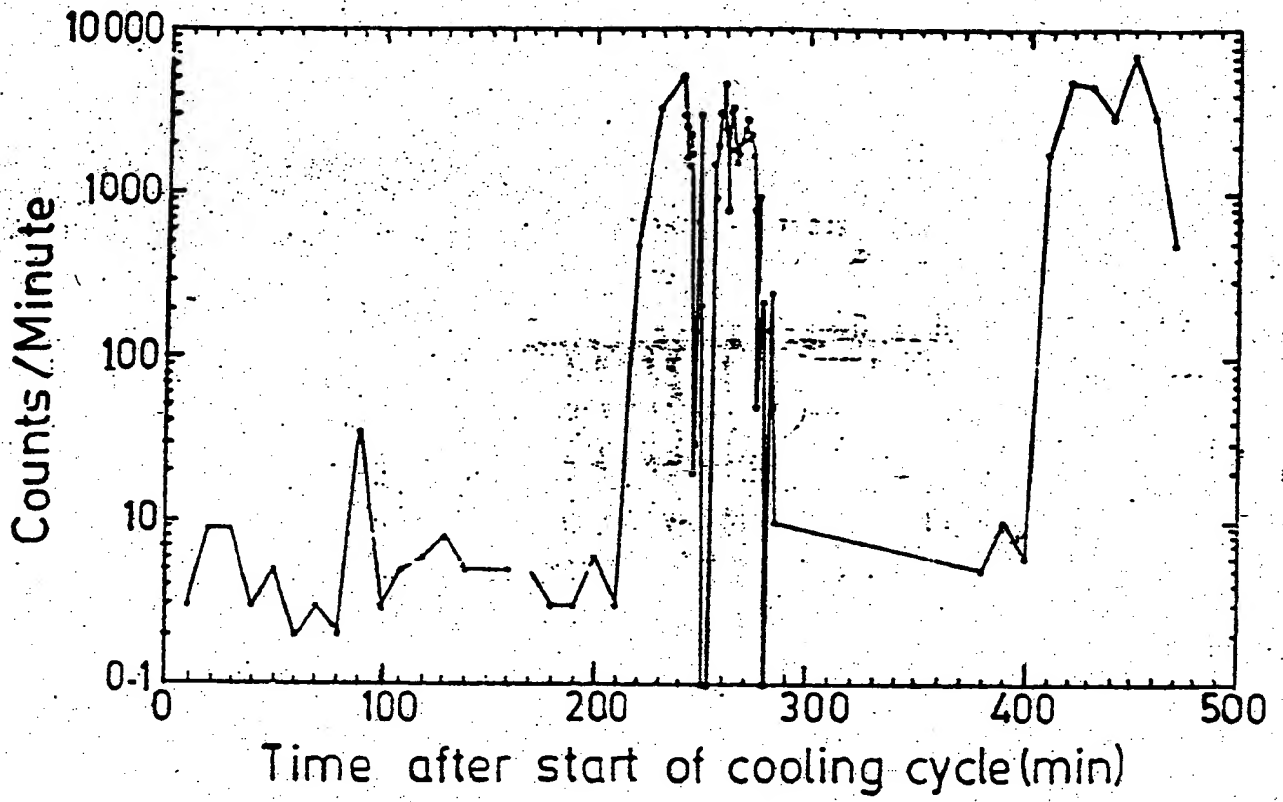


Fig.13 Count rate variation of 5 MeV tritons from a TiD_x foil
(From Cecil et al /95/)

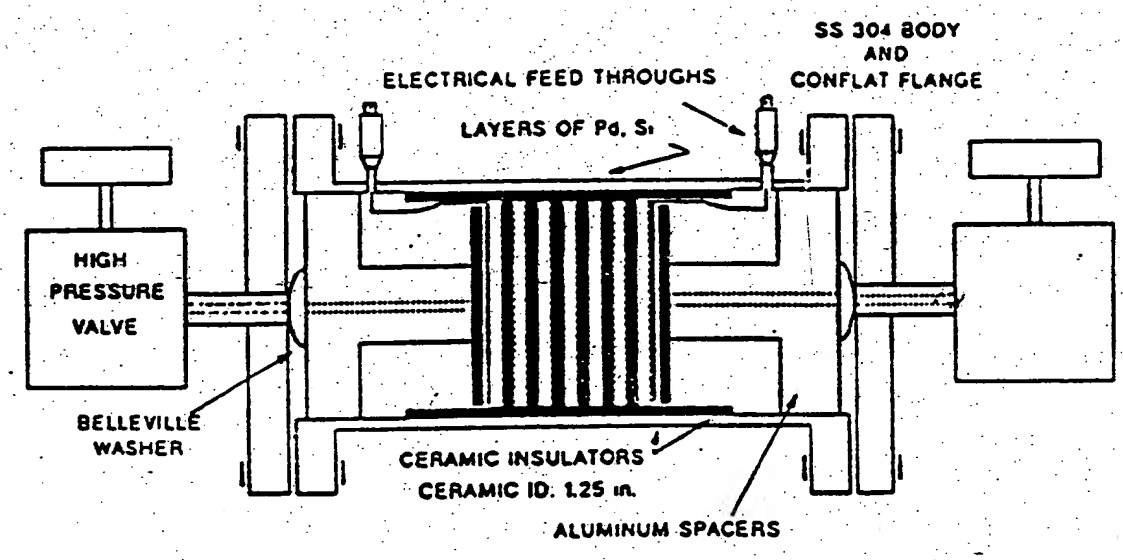
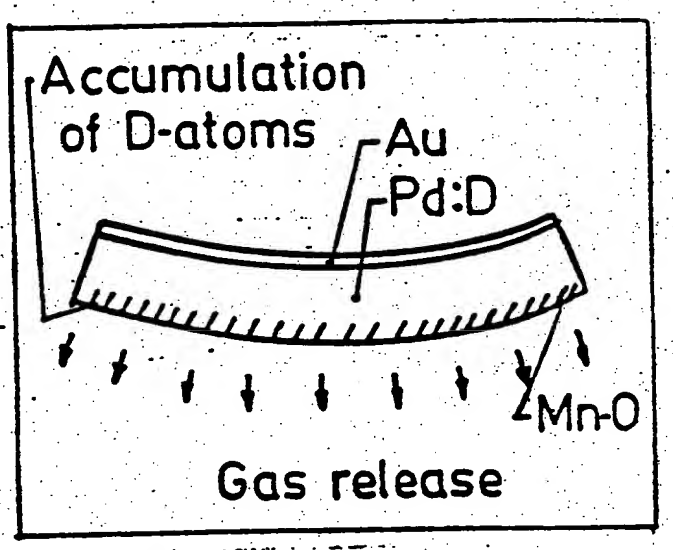


Fig.14 Solid state cell of Los Alamos (From Claytor et al /25/)



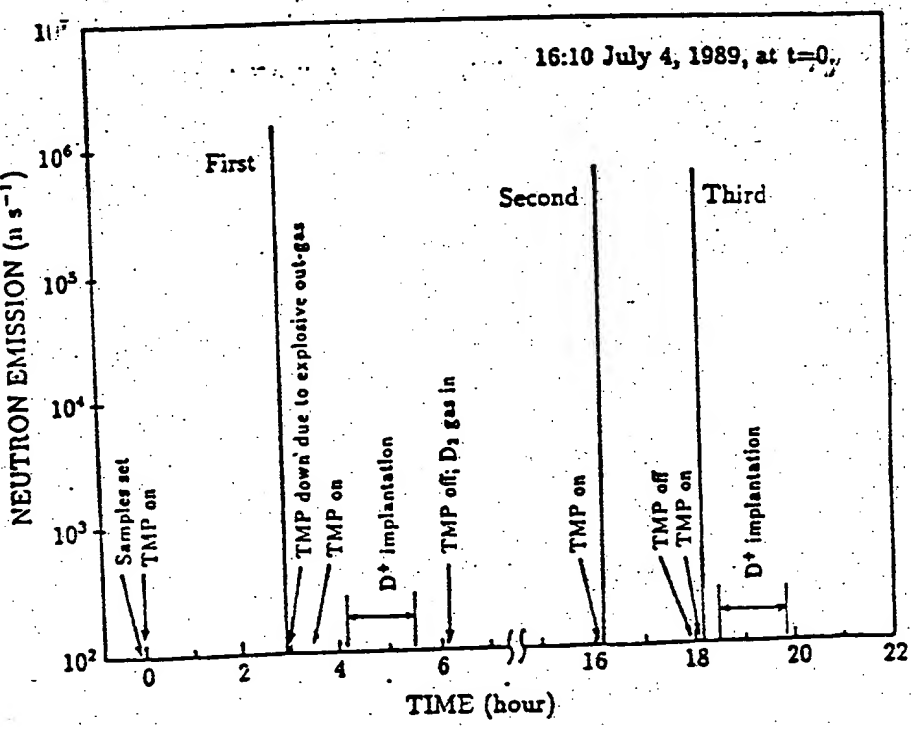


Fig.15 Burst Neutron Production from a deuterated Pd foil using a surface barrier device (From Yamaguchi et al /100/)

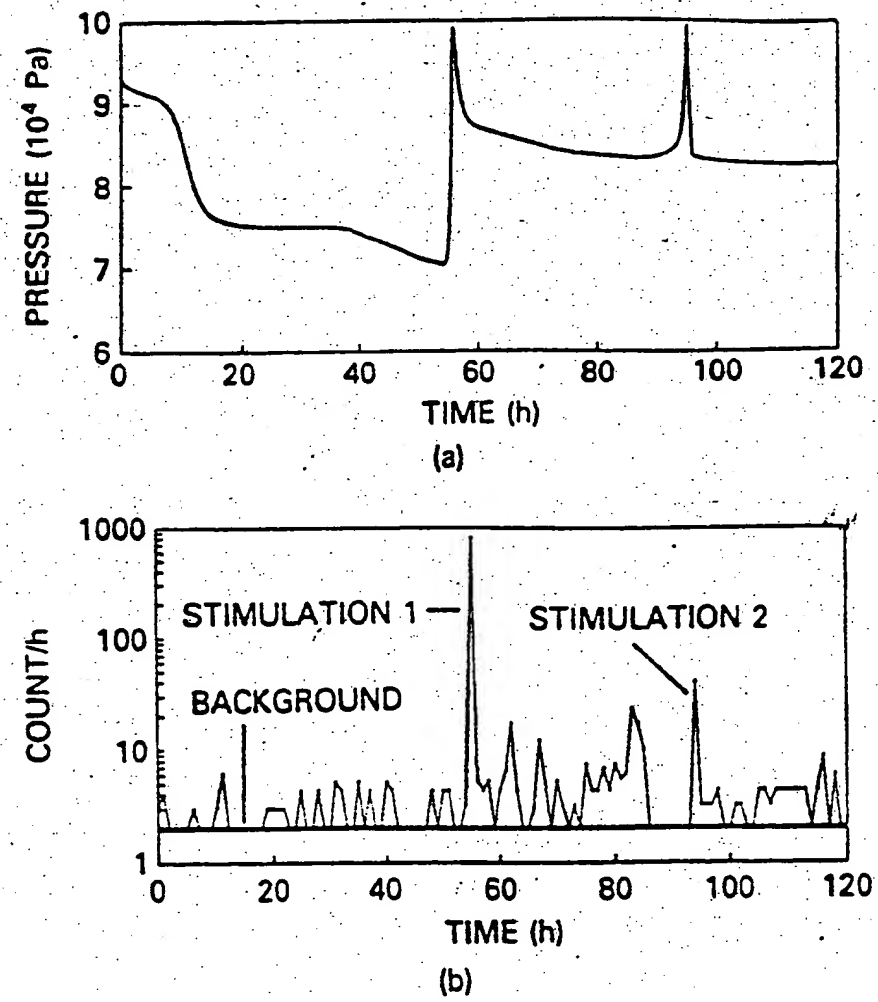


Fig.16 Neutron Production from D_2 gas discharge experiment using Pd Electrodes (From Wada et al /101/)

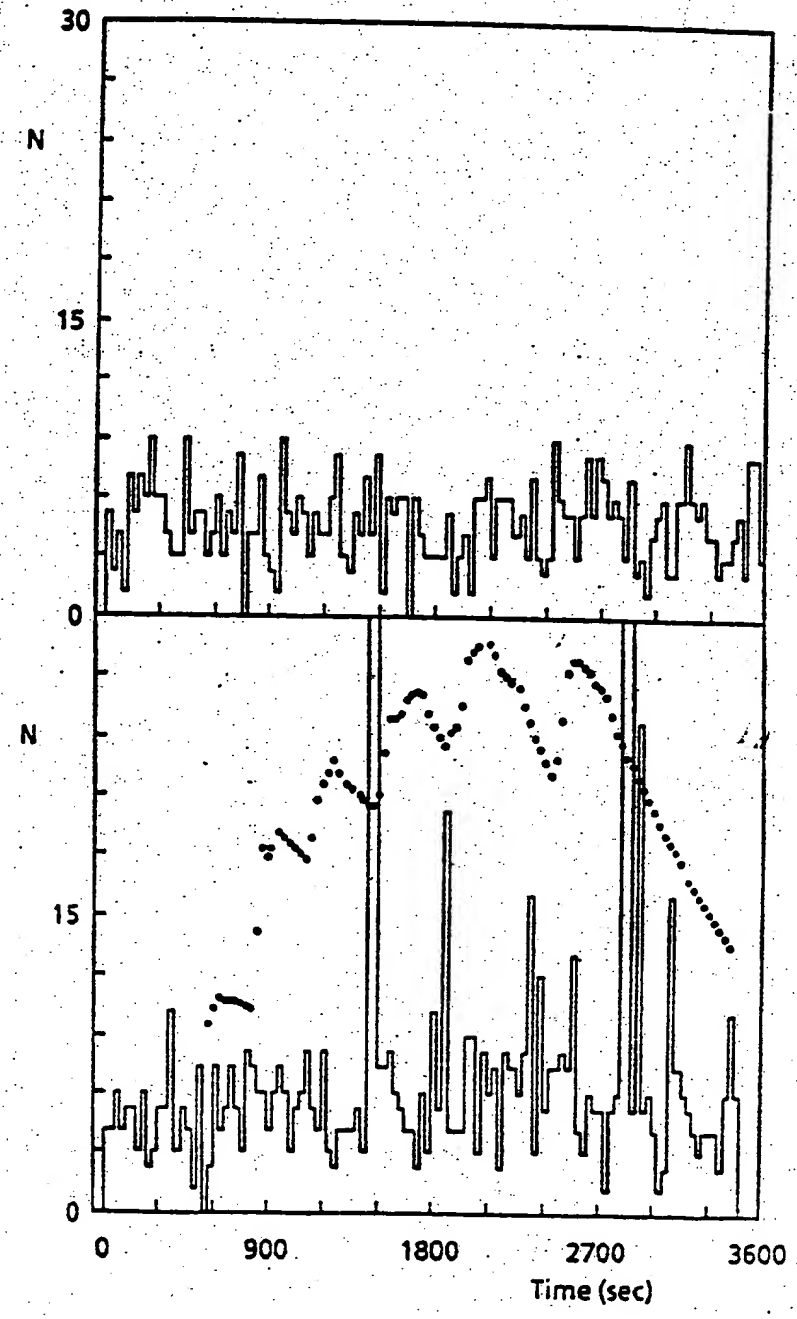
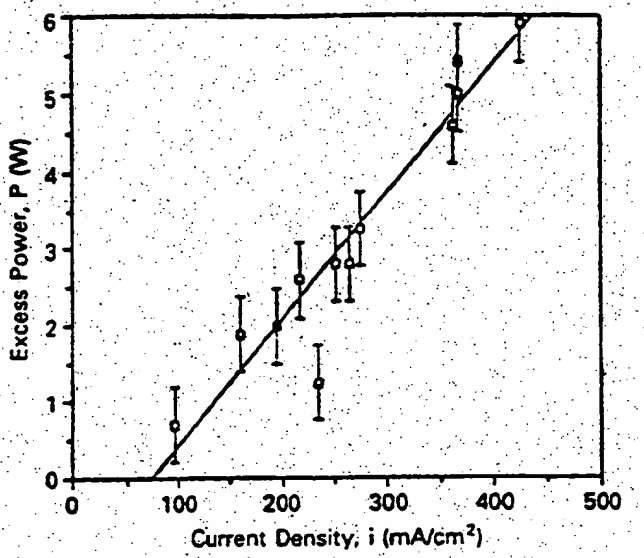


Fig.17 Neutron Emission in LiD-D_2O Experiment. Dotted graph in lower figure shows temperature variation (From Arzannikov et al /103/)



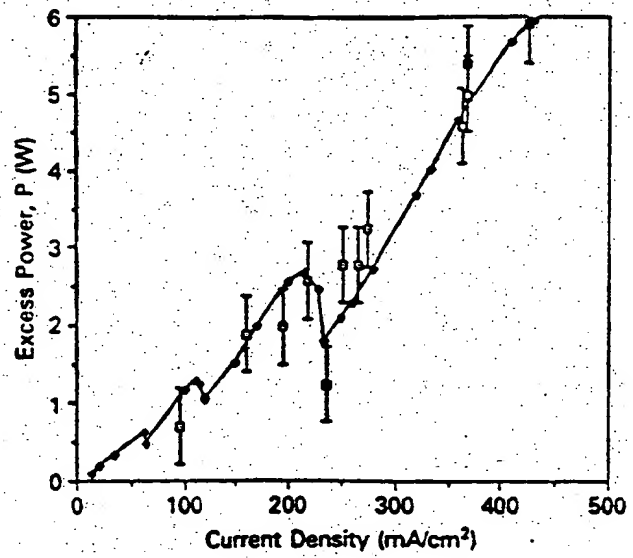


Fig.18 Example of fit of Bush's Model to experimental calorimetric data (a) Upper figure shows straight line fit ignoring low lying point as a bad data point. (b) Solid curve in lower figure shows TRM prediction (From Ref. /137/)

COLD FUSION

TECHNICAL NOTE

KEYWORDS: excess heat, cold fusion, closed system, internal recombiner

MEASUREMENT OF EXCESS HEAT AND APPARENT COINCIDENT INCREASES IN THE NEUTRON AND GAMMA-RAY COUNT RATES DURING THE ELECTROLYSIS OF HEAVY WATER

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Excess heat and apparent increases in the neutron and gamma-ray count rates have been observed in a series of tests performed at Oak Ridge National Laboratory to study the electrolysis of heavy water in the presence of palladium cathodes. For these tests, LiOD at a concentration of 0.1 to 1 N in D_2O was used in an insulated glass electrochemical cell in which the temperature was controlled and heat was removed by flowing water in a cooling jacket. Results of two of the tests, one of which lasted for over 1900 h, are reported. In the latter test, an internal D_2-O_2 recombiner was incorporated into the cell to give a closed system without off-gas.

Excess power, usually in the range of 5 to 10%, was detected for periods of many hours. Some of these events were initiated and could be extended by system perturbations. On three separate occasions, the mean neutron count rate exceeded the background by statistically significant values; one of these was apparently coincident with an extended period of excess heat generation. Increases in the gamma-ray count rates were apparently also coincident with two of the periods of excess neutrons.

INTRODUCTION

Several research groups have reported the measurement of excess energy during the electrolysis of heavy water containing LiOD as the electrolyte and in the presence of a palladium cathode.[1-5] In some cases, anomalous neutron count rates have been reported for such systems,[5-8] and increases of the tritium content of the electrolyte solutions have also been measured.[9] Researchers at Oak Ridge National Laboratory (ORNL) have carried out a series of electrochemical tests with the emphasis on careful measurements of as many parameters as possible. These included the simultaneous and continuous monitoring of both the heat balance and the neutron and gamma-ray count rates. Flow calorimetry was used in which flowing water in an insulated jacket around the electrolysis cell served to control electrolyte temperature and remove heat. In one extended test of over 1900 h, an internal catalytic system was used to recombine the electrolytically generated D_2 and O_2, resulting in a closed system without the need for release of any off-gas.

Excess heat and apparent increases in the neutron and gamma-ray count rates were observed.

MATERIALS AND METHODS

Although there has been almost a continuous evolution of the design of the electrochemical system used in these tests, two primary electrolysis cell designs were used. The first was an open system in which the electrolysis gases, D_2 and O_2, were allowed to continuously exit the cell. The second concept utilized an internal recombiner that catalyzed the recombination of D_2 and O_2 to form heavy water, which then returned to the electrolyte solution. The latter was a closed system that did not require replenishment of D_2O except when samples were withdrawn.

Open Electrolysis Cell

The open electrochemical cell that did not recombine the electrolysis gases was fabricated from Pyrex glass with a nominal inside diameter of 4 cm and an active internal height of 12.5 cm (Fig. 1). It had an ~4-cm-high internal gas space into which a N_2 purge gas could be introduced and removed. A 2.5-cm-thick Teflon cap was attached to a No. 40 Teflon O-ring connector and secured to the cell body by a clamp and a rubber O-ring. The cap accommodated the entrance of electrodes, a glass tube enclosing a thermocouple for measurement of electrolyte temperatures, a glass-encased resistor for internal heat calibration, and a polyethylene tube for introduction of makeup D_2O and removal of electrolyte samples. The cell was surrounded by an enclosed glass annulus with ~1 cm of open space through which water was forced to flow

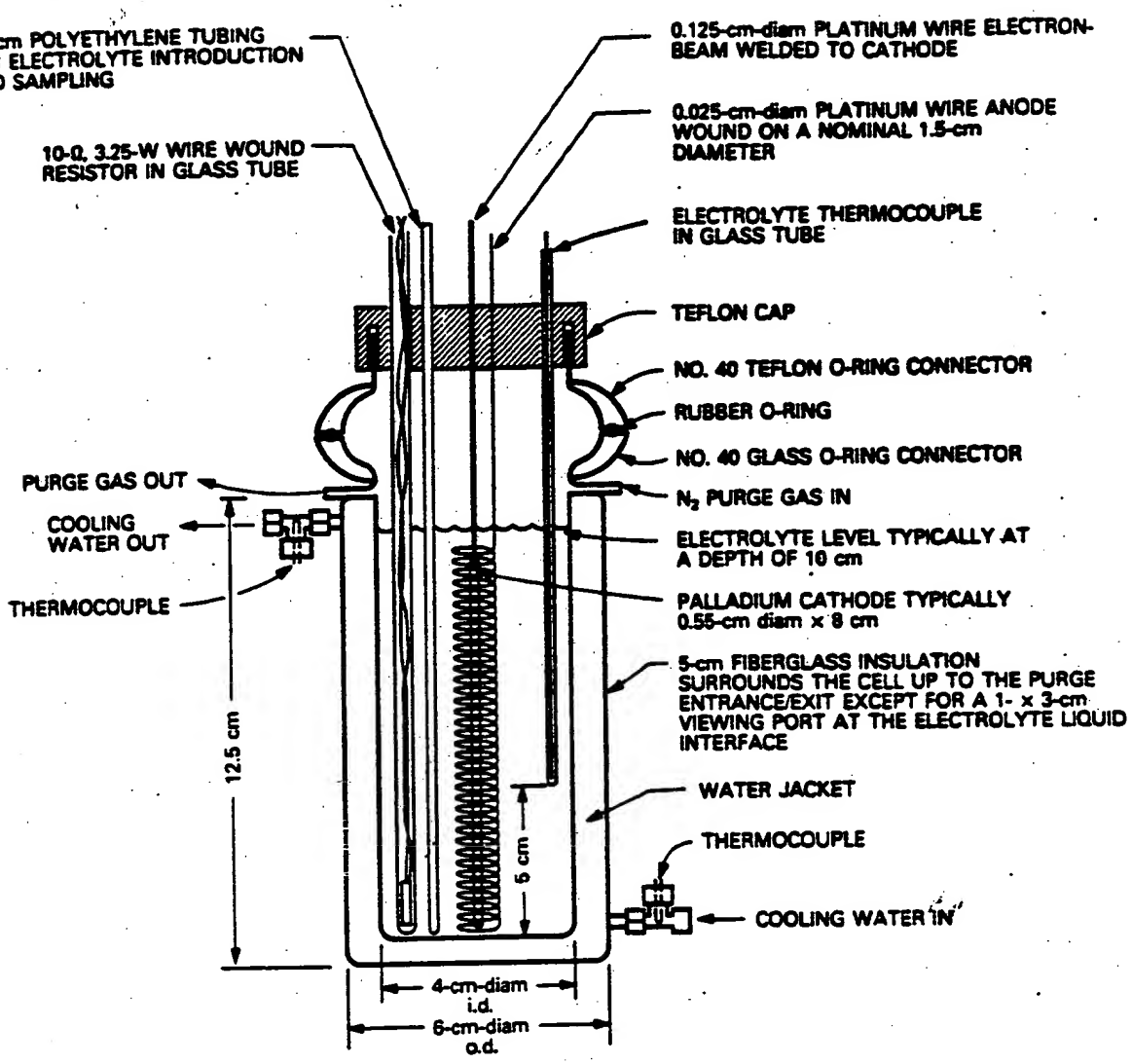

Fig. 1. Open-system cell with cooling-water jacket used for electrolysis tests.

by a metering pump. Thermocouples inserted in the cooling water inlet and outlet streams allowed the determination of temperature difference and, hence, heat flow. Fiberglass insulation that was 5 cm thick covered the entire exterior of the cell and top except for a 1- × 3-cm area that could be opened to observe the electrolyte level.

Closed Electrolysis Cell

The design concept for the closed cell was similar to that described above, except that the cell body was fabricated from nominal 1.5-in. Pyrex glass pipe, and the 1.25-cm-thick Teflon top was sealed with a conventional glass pipe flange (Fig. 2). As in the open system, a 1-cm annular water jacket was used for heat removal, and 5 cm of foam insulation surrounded by an additional 5 cm of fiberglass insulation was used to reduce unmeasurable heat loss. Typically, a 10-cm height of electrolyte solution was used, which resulted in a 9-cm height of gas space.

Total recombination of the evolved D_2 and O_2 was carried out within the gas space of the enclosed electrolysis cell. The catalytic recombiner was a 375-cm coil of 32-gauge platinum wire that had been electrochemically coated with ~10 wt% palladium black (see Fig. 3). The wire was wrapped around six Teflon-sheathed screws that were attached to the top flange and extended down into the gas space. Teflon tubing, connected through the flange to the gas space by conventional tubing compression fittings, exited through a heavy water bubbler so that any formation of off-gas could be detected. Similar gastight fittings were used for electrode connections and entrance of a Teflon electrolyte charging tube and a thermocouple sheathed in stainless steel.

Operation of the recombiner was initiated at the beginning of an experiment by imposing a 0.7-A (2.4-V) electrical current over a period of 2 to 4 h, after which no detectable off-gas from the system was observed. Following initiation, the recombiner electrical current was required only if the cell current had been stopped for an extended period and was then restarted.

The cooling jacket did not extend over the entire outside surface of the cell because space was needed for the glass pipe flanges. Thus, the recombiner section operated at a relatively high temperature as compared with the electrolyte. This resulted in heat loss at the top of the cell in spite of the 4 in. of insulation. A future design change will rectify this problem.

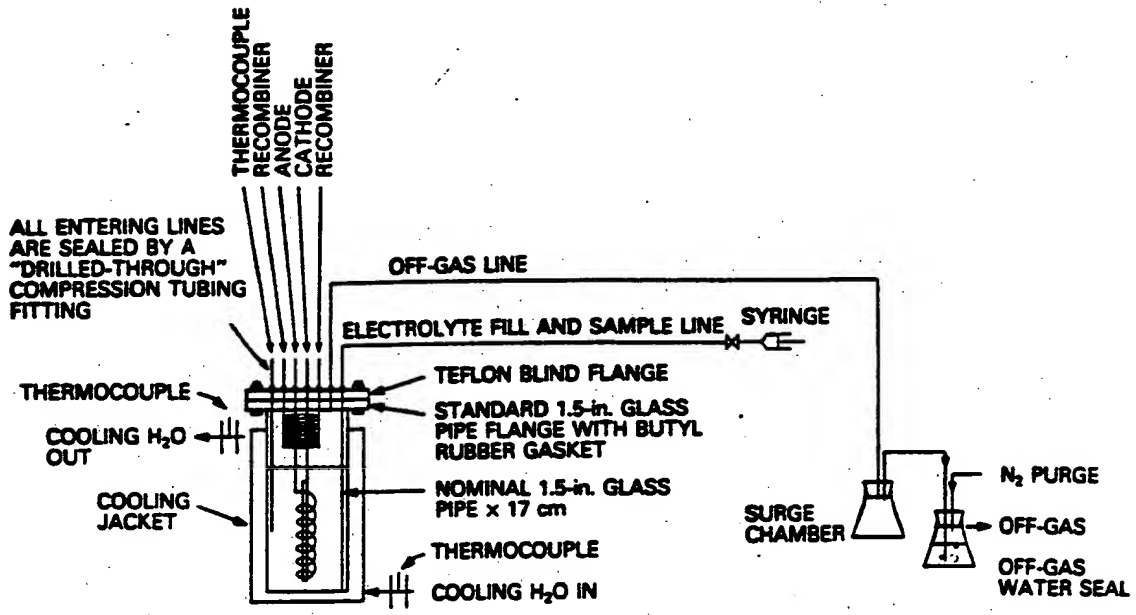

Fig. 2. Electrolysis cell and auxiliary equipment used for closed-system tests. The entire system is insulated with 4 in. of fiberglass insulation.

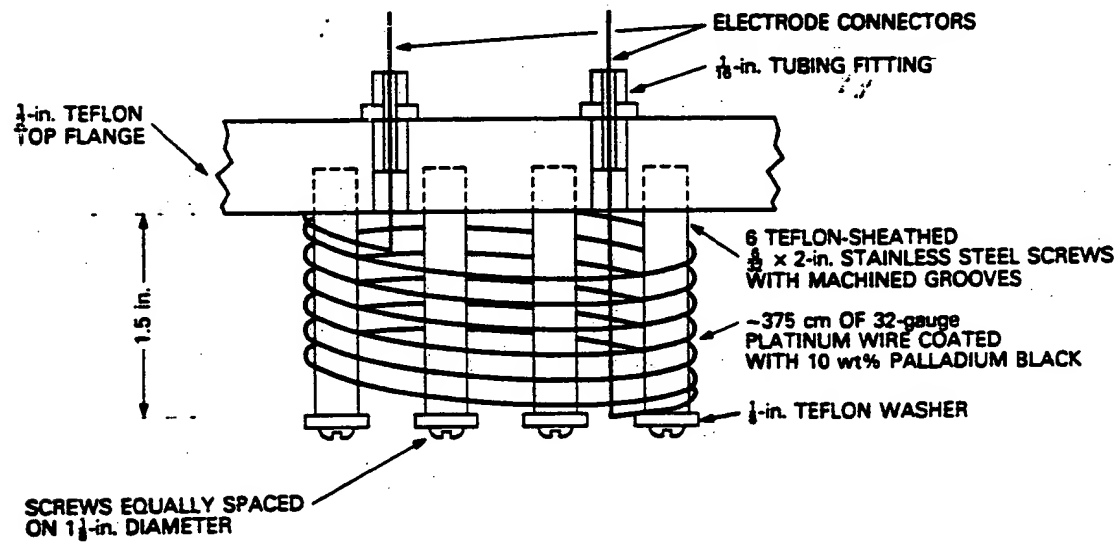

Fig. 3. Configuration of the recombiner used in the closed-system electrolysis cell.

System Design

The cooling water was supplied by a water reservoir with the temperature controlled to within ±0.1°C,[a] along with a positive-displacement pump[b] that controlled the coolant flow rate with an accuracy of 0.5 to 1% (Fig. 4). Nitrogen purge gas, when used, was monitored by a rotameter, while D_2O was added and electrolyte was sampled by a syringe pump connected to a Teflon tube that entered through the flange and extended to the bottom of the cell.

The electrical power[c] supply operated at a constant current that was measured by a Keithley 171 microvolt DMM meter[d] with an accuracy of ±1 mA. Electrolyte and coolant water inlet and outlet temperatures were measured by calibrated thermocouples (temperature differences were generally in the range of 2 to 5°C), and the overall electrode voltage was determined to within 0.001 V by a Keithley 181

[a]Polystat Model 1194-00, Cole Parmer Instrument Company, Chicago, Illinois.
[b]Duplex Pump Model RP2, Penn Systems, Inc., Broomall, Pennsylvania.
[c]Princeton Applied Research, Model 371, Potentiostat/Galvanostat.
[d]Keithley Company, Cleveland, Ohio.

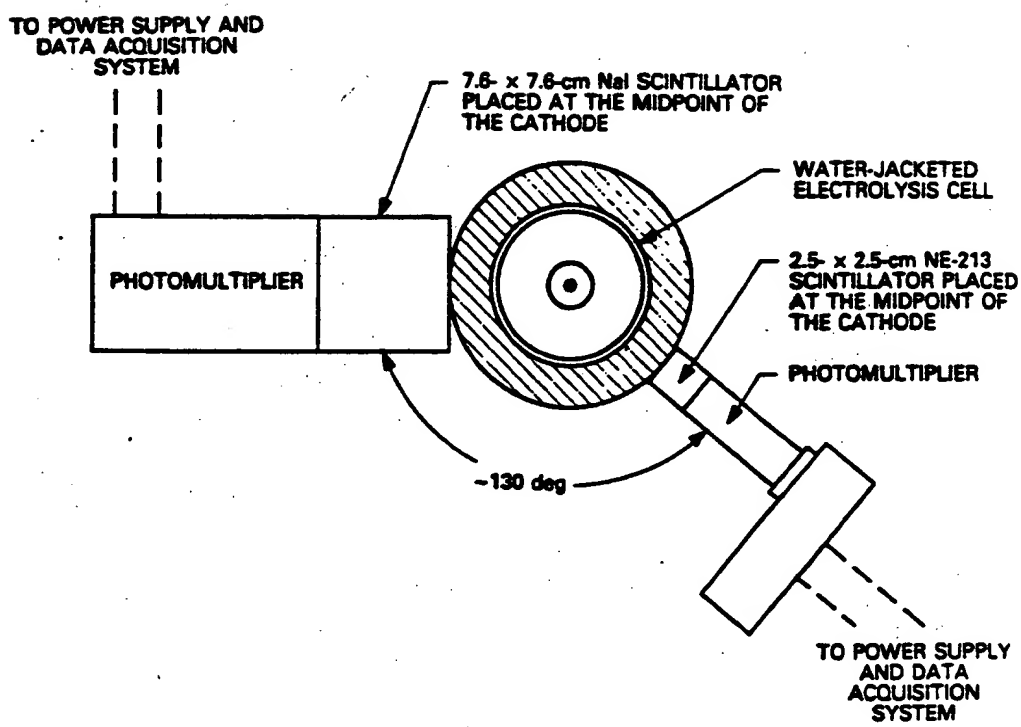

Fig. 5. Placement of scintillation detecting systems used for detection of neutrons and gamma rays.

reagent-grade natural lithium in the D_2O at a nominal concentration of 0.1 to 1.0 *N*.

The cathode material was 99.9% palladium[h] that had been cast under argon and then swaged to the desired diameter. This cylindrical material was cut to the desired length; a 0.13-cm platinum connecting wire was electron beam welded to the top; and the metal assembly was then annealed at 900°C for 2 h in vacuum. All of the anode material and the recombiner were fabricated from 99.9+% platinum wire in the size range of 24 to 32 gauge.[i] The anodes consisted of wire coils made by wrapping the wire around the exterior of a skeletal glass mandrel (four 0.15-cm-diam glass rods with cross bracing) that surrounded the cathode and provided an electrode spacing of 0.3 to 0.5 cm.

Operating Procedures

The tests were initiated by loading the prepared electrolytic cell with ~125 ml of the electrolyte, starting the purge gas at ~1 ml/s for the open cell, and turning on the electrical current. A purge gas was not used with the closed system, and D_2-O_2 recombination was initiated by electrically heating the wire coil prior to the accumulation of a large amount of electrolysis gas in the headspace. This initiation heat was not required after the catalytic reaction started, at least in the current range of 0.71 to 4.26 A.

The temperature of the electrolyte was controlled by the cooling water temperature and flow rate and was usually maintained in the range of 28 to 38°C; however, some controlled excursions were imposed up to 70°C and down to 24°C. Makeup D_2O was added to the electrolyte either continuously with a syringe pump or batchwise every 8 h to maintain a constant electrolyte inventory for the open-system test, a electrolyte samples were taken periodically (every 2 to 3 day The gamma-ray and neutron count rates were measured cc tinuously and recorded every 4 h.

Energy Balance

An energy balance expressed as power out versus pov in was determined for each test, based on the following sumptions:

1. The electric current is 100% efficient for the electr ysis of D_2O.
2. The system operates at quasi-steady state with a c stant inventory of deuterium in the cathode.
3. Except where internal recombination is used, all of D_2 and O_2 exit the electrolysis cell without recom nation.
4. The exiting gases, including a purge gas (if used), saturated with D_2O that is at equilibrium with hea water at the temperature of the electrolyte.
5. There is no heat loss to the ambient environment

The second assumption is obviously not correct whe major portion of the formed D_2 is being adsorbed by cathode, but this is true for only a short period in the ea phase of the test. Since the volume of makeup heavy wa required to be added to maintain a constant inventory in electrolysis cell was approximately equal to the volume el trolyzed and evaporated for the open systems, it was assur that very little recombination of the electrolysis gases curred. Conversely, no addition of D_2O or electrolyte v required for the closed systems with recombination excep replace electrolyte samples that were withdrawn. Alth

[h]Materials Research Corporation, Orangeburg, New Jersey.
[i]Engelhard Corporation, Iselin, New Jersey.

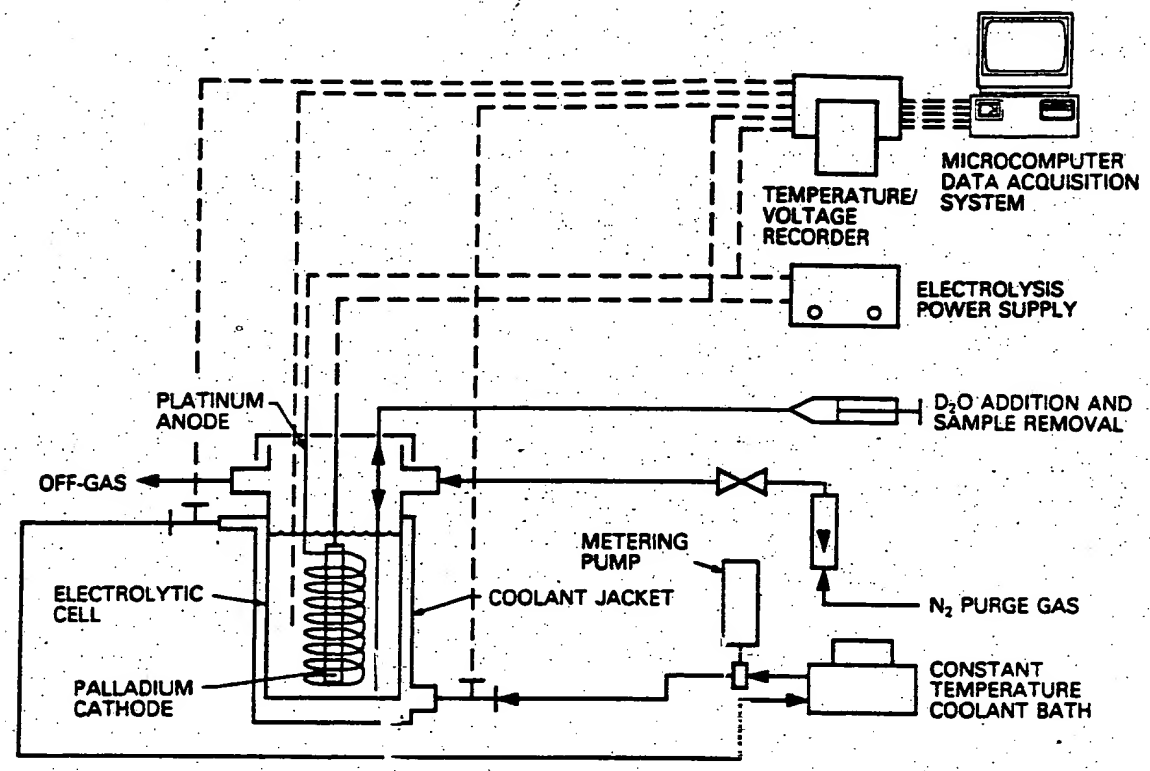

Fig. 4. Integrated system components used in the electrolysis tests.

nanovoltmeter.[d] These system parameters, along with all measured temperatures, were recorded on a strip-chart recorder typically every 10 s, and average values based on ten data points were recorded on a microcomputer data acquisition system every minute. Calibration of the thermocouples, including curve fitting by fourth-order polynomials, allowed temperature measurements to be made to within 0.05 to 0.1°C. The data acquisition system also calculated a heat balance at 1-min intervals with an estimated experimental error calculated to be typically 0.2 W.

Radiation Detection

The experimental apparatus was contained within a 2-ft-thick concrete enclosure in an attempt to reduce the neutron background. Neutron levels were measured by a 2.5-cm-diam × 2.5-cm NE-213 scintillator[e] placed immediately adjacent to and at the midpoint of the insulated electrolysis cell (Fig. 5). Necessary electronics were used to allow pulse-shape discrimination with a neutron threshold of −1.2 MeV. This arrangement also allowed the measurement of gross gamma rays with an energy level greater than −0.3 MeV. The NE-213 scintillator is sensitive to both neutrons and gamma rays; during calibration, it was determined that there was a gamma-ray contribution to the neutron peak of −4.1% of the gamma peak, or −20% of the neutron peak. All reported neutron count rates were corrected for this contribution. The overall counting efficiency was 1.46×10^{-3} as determined by a ^{252}Cf source, and the neutron detector had a typical sensitivity at three standard deviations equivalent to 3×10^{-24} fusion/deuterium pair per second.

A separate gamma-ray spectrometer utilizing a 7.6-cm-diam × 7.6-cm NaI detector[f] was also used. The detection head was placed immediately next to the midpoint of the insulated cell and at an orientation −130 deg to the NE-213 detector. Although there was no efficient provision for interacting possible neutrons with protons in order to detect the resulting gamma rays, the 1 cm of water in the cooling jacket of the cell should result in some indication. A multichannel analyzer that covered an energy range of 0.14 to 5.20 MeV was used, and the system had an overall detection efficiency of 5.75×10^{-5} as determined by a ^{252}Cf source with a polyethylene converter. The NaI system had somewhat less sensitivity than the neutron detector to possible fusion reactions because of the higher gamma-ray background. The neutron and gamma-ray spectra were periodically recorded on magnetic media by a small computer system.

The tritium concentration in the electrolyte was measured at definite intervals by removing a small volume of the electrolyte and counting with a liquid scintillation system. The accuracy of each measurement was ±200 Bq/ℓ.

Materials

The heavy water used in the experiments was deuterium oxide D_2O (99.9 at.% deuterium) with a low tritium content, −2000 Bq/ℓ.[g] The electrolyte was prepared by dissolving

[e]Nuclear Enterprises, Inc.

[f]Harshaw Chemical Company, Solon, Ohio.

[g]Aldrich Chemical Company, Inc., Milwaukee, Wisconsin.

the system was well insulated, some heat loss obviously occurred to the ambient, but this would result in a conservative estimate of the recovered heat. Necessary chemical and physical properties for D_2O were obtained from a reference handbook.[10]

Open System

The resulting energy balance for the open systems can be represented by

POWER IN: (volts) × (amperes);

POWER OUT:

ELECTROLYSIS (typically >30%)

$D_2O \rightarrow D_2 + \frac{1}{2}O_2$ (− heat of formation);

FORCED COOLING (typically >60%)

(cooling water temperature increase) × (flow rate);

LATENT HEAT (typically <2%)

(heat of D_2O vaporization).

Closed System

The closed system with recombination allows a much simpler energy balance with fewer assumptions:

POWER IN:

(volts × amperes);

POWER OUT:

(cooling water temperature increase) × (flow rate).

EXPERIMENTAL RESULTS

As in the case of earlier tests at this laboratory,[4,5] excess power was detected during certain periods. In addition, an apparent coincidence of a higher neutron count rate and an increase in the gamma-ray count rate were observed in one test.

Operating Parameters

During the tests, conditions of quasi-steady state were often maintained for many hours at a time; however, significant changes in the operating parameters were made at various times (Figs. 6 and 7). These changes were carried out in an attempt to determine conditions that would initiate or maintain the generation of excess power and/or the products of nuclear interactions. Parameter changes included cathode current density, electrolyte (LiOD) concentration, and the electrolyte temperature that was brought about by a change in the cooling water flow rate and temperature.

The same type of systematic increase in the cathode current density was imposed during the closed-system test; however, there were also periods of current density cycling in which rather severe system instability was imposed (Fig. 7). These included the interval of 1005 to 1170.5 h in which the cathode current density was cycled between 100 and 400 mA/cm^2

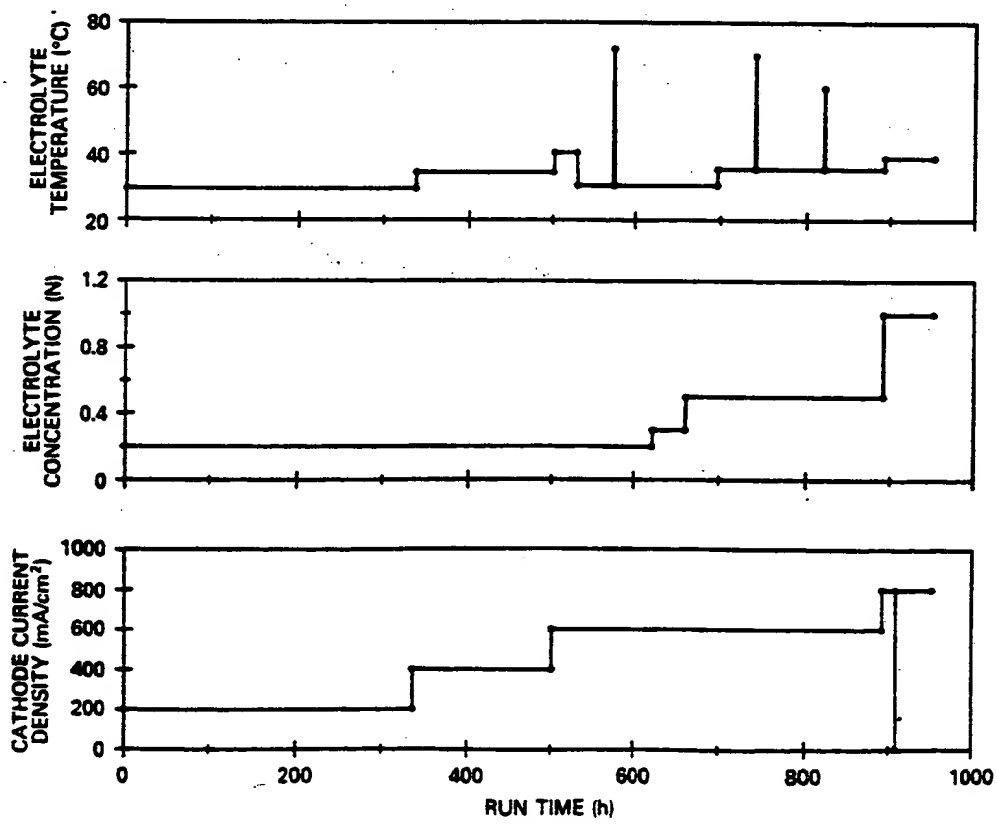

Fig. 6. Major variations of the controlled operating parameters (cathode current density, electrolyte concentration, and electrolyte temperature) during the open-system test.

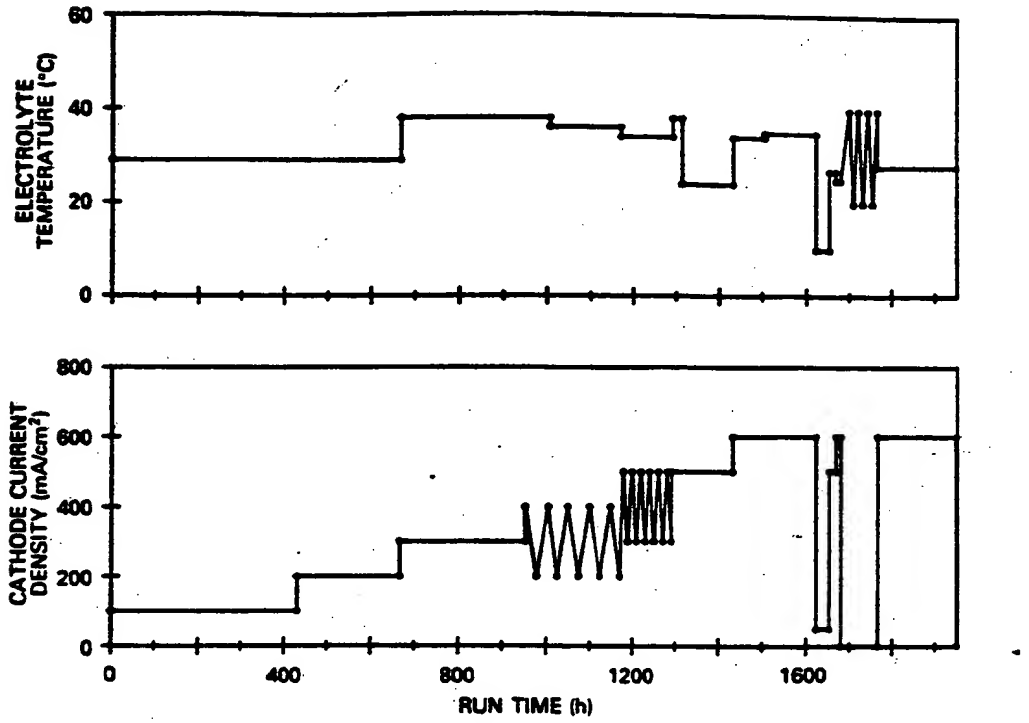

Fig. 7. Major variations of the controlled operating parameters (cathode current density and electrolyte concentration) during the clos system test.

for a cycle period of 66 min; this was followed by a second interval of cycling between 300 and 500 mA/cm^2 with a period of 5.7 min.

There appeared to be a small, but progressive, decrease in the LiOD concentration during each test, apparently due to the deposition of this material on surfaces in the vapor space. Such deposits resulted in a slow increase in both the cell voltage and the power input. To accommodate this effect, the LiOD concentration was periodically checked and occasionally modified with makeup electrolyte when samples were taken. These changes were usually small, but they could result in measurable decreases in the cell voltage and power input.

Excess Energy

Several periods of apparent excess energy have been observed in tests in both the open and closed systems. Some of these were seemingly spontaneous when the system was operating at a quasi-steady state, while others of longer duration were initiated and maintained by system perturbations.

Open System

During the first 540 h of operation, there were successive increases in the cathode current density up to a level of 600 mA/cm^2, but the power balance (rate of energy out minus rate of energy in) was essentially zero within the calculated experimental error. The calculated experimental error was predominantly due to the uncertainty in the temperature measurement (±0.1°C) and the cooling water flow rate (1%).

At ~540 h, heat in excess of that provided by inlet electrical power was apparently initiated by a decrease in the electrolyte temperature (Fig. 8). During the next 300 h, the power excesses ranged as high as 11% (well outside the experimental error of ~3%); but, after a few hours, it tended to fa away. Increases in the electrolyte concentration or changes the electrolyte temperature appeared to again enhance the ergy excess. The electrolyte temperature variations seemed be the most effective means for maintaining excess pov with either a reduction in the temperature or rapid cycling the temperature to 60 to 70°C and back to the original val Ultimately, the energy balance became negative when cathode current was increased to 800 mA/cm^2. This w probably due to increased heat loss to the environment. short cycle of the cathode current to zero and back to original value also had no lasting effect.

Closed System

It became obvious during the closed-system test that th was a loss of heat to the environment, primarily through top flange. This loss was apparently due to the relatively hi temperature associated with the recombination and the la of positive heat removal by the cooling water on the t flange. (The temperature of the outside of the top flange w usually in the range of 50 to 60°C.) Based on subsequent c ibration tests, it was estimated that 1 to 3% of the generat heat was lost to the environment and was not recovered the cooling water, even after additional insulation had be added to the system at ~150 h into the test. This heat loss w not introduced into the heat balance calculations; therefo the reported values of heat removal were very conservati Although more precise experimental measurements w made in this test, the major contributors to the experim tal error were still the measurement of temperatures with c ibrated thermocouples (±0.05°C) and the control of cooli water flow rate (±0.5%).

The power balance was essentially even or somewhat n ative during the first 740 h of operation (Fig. 9). Follow

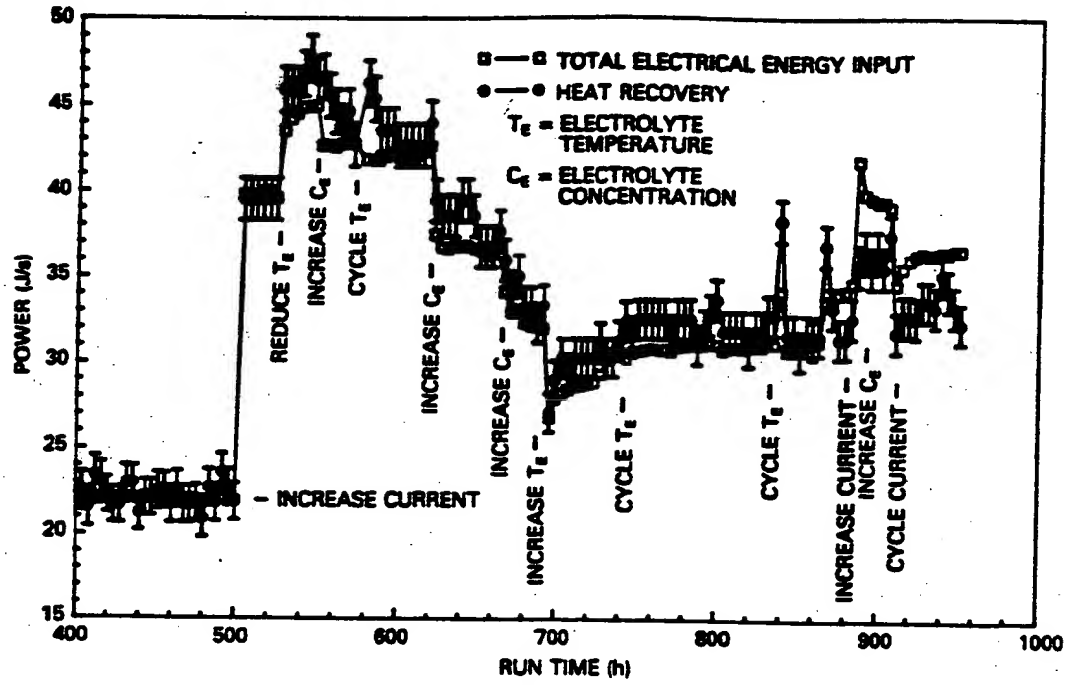

Fig. 8. The power balance during periods of excess power initiated by changes in operating parameters during the open-system test. Each point represents the mean value of 30 measurements during a 4-h interval, and the error bars represent calculated uncertainty in the experimental values based on independent calibration of temperature and flow metering systems.

that interval, there were two major periods of spontaneous excess power, each of which lasted for several hours (Fig. 10). These were relatively modest excesses with maximum values of ~6% but well above the calculated experimental error of ~1 to 2%.

Cycling of the cathode current appeared to have little effect on the generation of excess energy, but an extended period of excess power was initiated at ~1320 h by a decrease in the electrolyte temperature from 38 to 24°C (Figs. 9 and 11). During this period, the power excess was generally in the range of 5 to 10%, with an estimated experimental error of 1 to 2%.

For this period of over 300 h of excess energy, the cathode current density was increased to 600 mA/cm^2 and, for a short time, was decreased to 50 mA/cm^2 with only limited effect. The electrical current was then stopped for ~100 h while additional heat calibration tests were made. When the cell current was again initiated, the excess energy persisted at about the same level.

At ~1780 h, the cathode current was stopped momentarily, and the heavy water electrolyte (D_2O-LiOD) was replaced by a comparable light water system (H_2O-LiOH). To ensure that most of the D_2O was removed, the electrolyte inventory was completely replaced twice. As expected, removal of the heavy water resulted in a decrease in the power excess to approximately power balance, but this required over 100 h (Figs. 9 and 12). Perhaps this means that the energy-producing process was a bulk phenomenon that required a significant replacement of ^2H with ^1H within the palladium cathode to "turn off" the excess heat generation.

Detection of Products of Nuclear Interactions

During the open-system test, no anomalous count rates were observed for neutrons or gamma rays on either the NaI or NE-213 detection systems. In particular, the neutron count rate from the NE-213 detector remained at about the level of the predetermined neutron background (40 neutron count/24 h) for the entire duration (1300 h) of the test. However, in the closed-system test, there were small, but significant, increases in both the fast neutron and the gamma-ray count rates from the NE-213 system and, at some energy levels, in the gamma-ray count rates from the NaI scintillation system (Table I and Fig. 9).

Neutrons

Unexplained increases in the fast neutron count rate were observed in three significant periods of the closed-system test (Fig. 9). The first of these occurred during a 72-h period around 400 h from the start of the test in which the mean neutron count rate increased 57% above the previously determined background level and 27% above the immediately preceding mean count rate. The 95% confidence level of the higher neutron count rate, as shown in Fig. 9, indicates that this was statistically significant. This observation was made during a time of apparent modest excess power that was at a level well within the experimental error.

The second important interval of increased neutron count rate was initiated and continued for 96 h during the second cyclic operation of the cathode current density in which a cycle period of 5.7 min was used. This was the most significant increase in the mean neutron count rate, resulting in a level that was 76% greater than the background and 54% greater than the immediately preceding level. This was again a statistically significant increase.

The longest period of apparent increase in the neutron count rate lasting ~300 h started a few hours after initiation of the extended period of excess power that began at ~1330 h from the beginning of the test as an apparent result of the decrease in electrolyte temperature (Fig. 9). The maximum mean value was 69% greater than the background level and

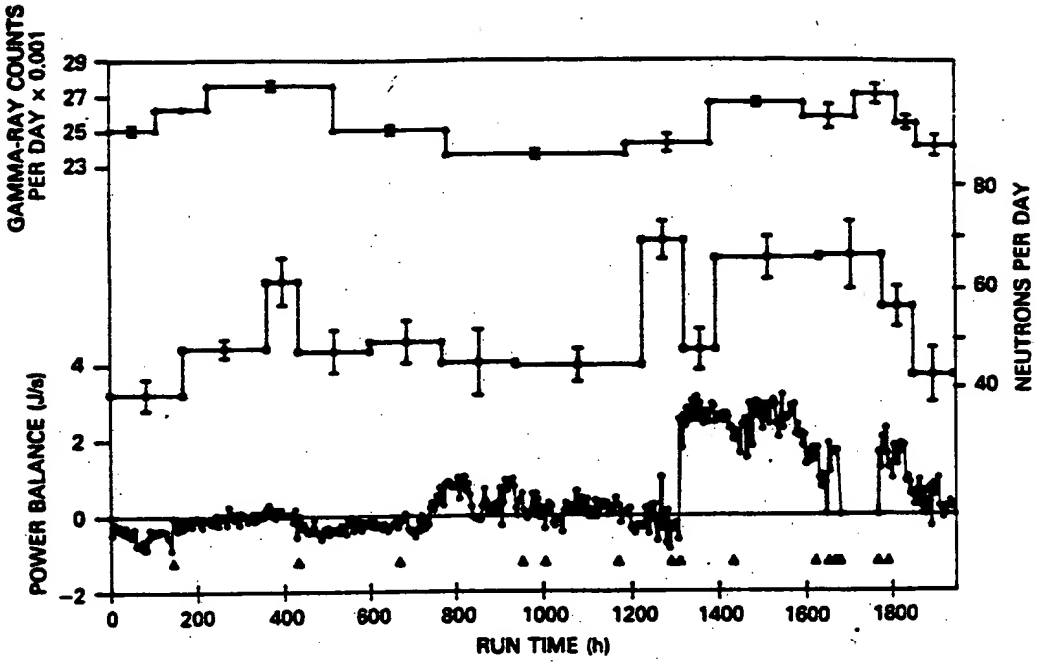

Fig. 9. Important experimental measurements during the closed-system test. The lower curve is the power balance, with each point representing the mean value of 30 measurements during a 4-h interval; the middle curve represents the mean value of the daily neutron count rate over the period indicated; and the upper curve represents the mean value of the daily gamma-ray count rate over the period indicated for the energy range of 2.64 to 3.14 MeV from the NaI system. The error bars in the upper two curves are the 95% confidence levels of the indicated mean values of the counting rates. The open triangles represent significant changes in the operation of the system, including 144 h—increase insulation; 431, 667, and 953 h—increase cathode current density from 100 to 200 to 300 to 400 mA/cm^2, respectively; 1005 h—initiate cyclic cathode current density varying from 200 to 400 mA/cm^2 with a 66-min period; 1170 h—initiate cyclic cathode current density varying from 300 to 500 mA/cm^2 with a 5.7-min cycle; 1291 h—maintain cathode current density constant at 500 mA/cm^2; 1312 h—reduce the electrolyte temperature from 38 to 24°C; 1132 h—increase cathode current density to 600 mA/cm^2; 1623 h—reduce cathode current density to 50 mA/cm^2 and electrolyte temperature to 10°C; 1653 h—increase cathode current density to 500 mA/cm^2; 1669 h—increase cathode current density to 600 mA/cm^2; 1694 to 1766 h—carry out energy calibration tests; 1766 h—initiate electrolysis at a cathode current density of 600 mA/cm^2; and 1790 h—replace electrolyte with LiOH-H_2O.

38% higher than the immediately preceding mean value of the neutron count rate, a statistically significant increase. As in the case of the excess power, this neutron count rate began to decrease when the heavy water was replaced with light water and essentially reached background level by the end of the test. This higher level of the neutron count rate persisted even during the time when the electrical current was turned off for heat flow calibrations. Incidentally, Sanchez et al.[8] also observed high neutron levels for a few hours after the electrical current had been turned off in their experiments. There was no indication that the extended observed increases in the neutron count rate were the result of a general environmental increase.

Gamma Rays

Variation in the count rates of gamma rays determined by both the NE-213 scintillation system and the NaI system (at least up to energy levels of 3.6 MeV) also appeared to have small, but statistically significant, increases. Since the NaI spectra involved higher count rates and better statistics, a more detailed analysis was possible. For that system, the gamma-ray spectra from each 4-h-long counting period were divided into ten equal energy segments, with each segment spanning an energy range of ~0.520 MeV (Table I). The most significant increases in the gamma-ray count rate occurred in the energy range of 2.64 to 3.14 MeV; therefore, mean values of the count rate for this range have been included in Fig. 9, where they can be easily compared with the neutron count rates and excess power. There were apparent coincidences of increased gamma-ray count rates with the first spontaneous neutron increase around 400 h of operation and for the final neutron increase that occurred during the extended period of excess power starting at −1320 h (Table I and Fig. 9).

Surprisingly, there were no statistically significant increases in the gamma-ray count rate in the 2.12- to 2.63-MeV energy region (the energy level where gamma rays are emitted from neutron interactions with protons); however, all other energy bins less than that range showed an apparent increase during the extended period of excess power. There was no indication of increased gamma-ray count rates above an energy level of 3.14 MeV, at least up to 5.2 MeV.

These extended periods of increased gamma-ray count rates could not be explained by environmental variations, such as the local barometric pressure or ambient temperature, and there was no apparent change in the instrumental threshold or preamplifier gain. Characteristics of the changes in the gamma-ray energy spectra are also not consistent with interference from electrical noise or from an external radiation source since the variations are relatively long term and do not occur as narrow peaks.

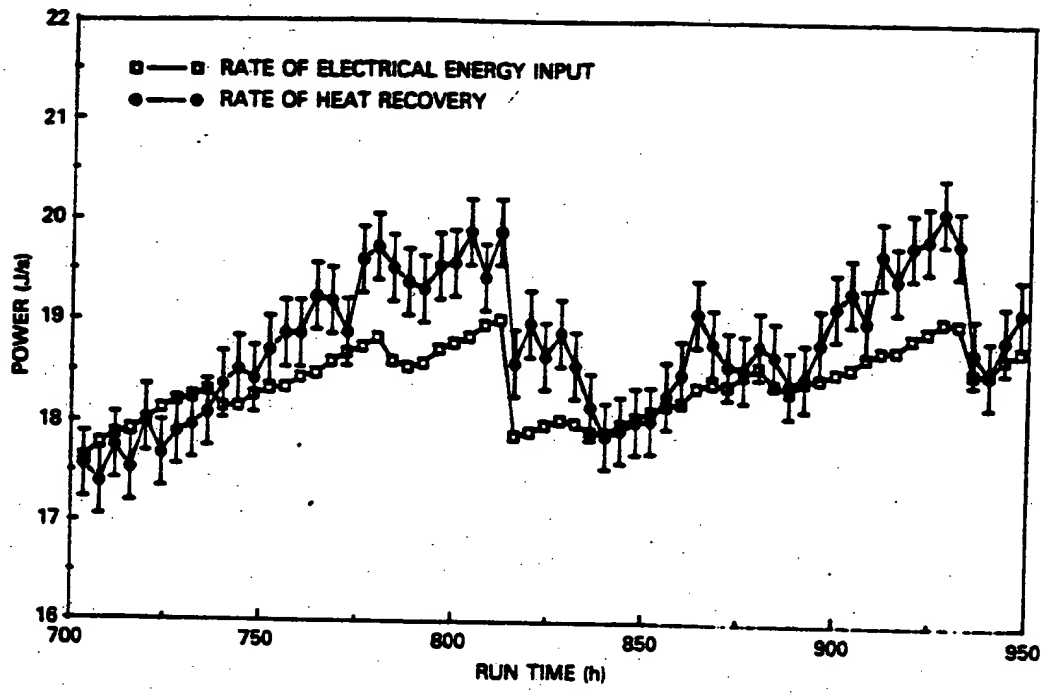

Fig. 10. Power balance in the closed-system test during the period when two major periods of spontaneous excess power were observed. The variation in the rate of energy input was primarily due to changes in cell voltage that resulted when the electrolyte concentration was periodically adjusted. Each point represents the mean value of 30 measurements during a 4-h interval, and the error bars represent the maximum calculated uncertainty in the experimental values based on independent calibration of temperature and flow metering systems.

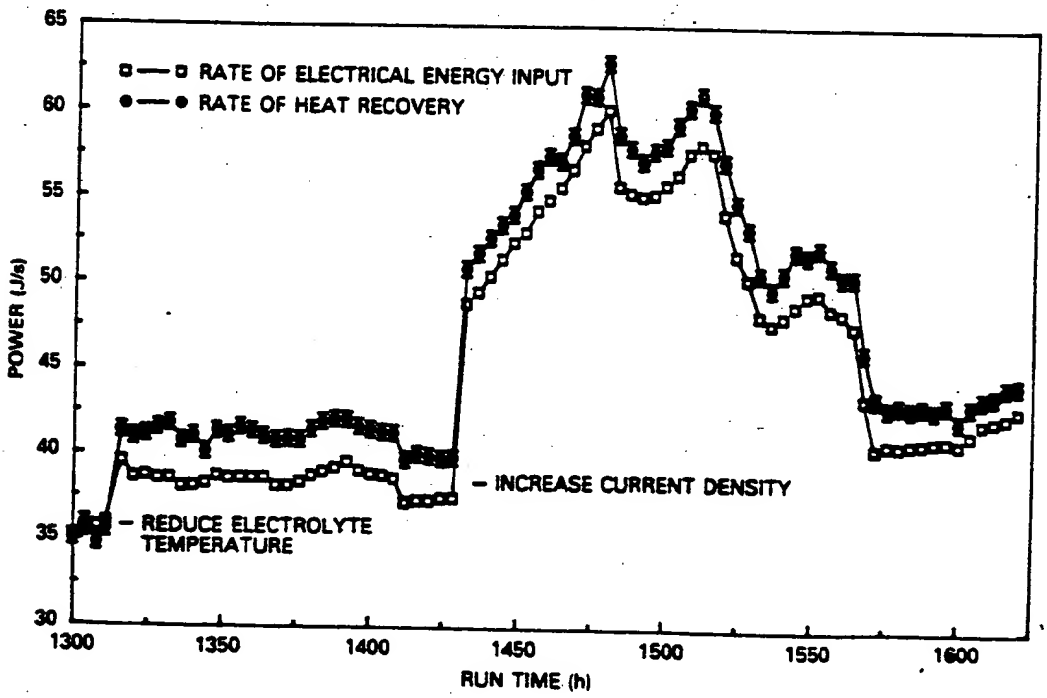

Fig. 11. Power balance in the closed-system test during the period where extended excess power was initiated by the reduction in electrolyte temperature. Variations in the rate of energy input were due to changes in the electrolyte temperature, increase in cathode current density, and periodic adjustments to the electrolyte concentration. Each point represents the mean value of 30 measurements during a 4-h interval, and the error bars represent the maximum calculated uncertainty in the experimental values based on independent calibration of temperature and flow metering systems.

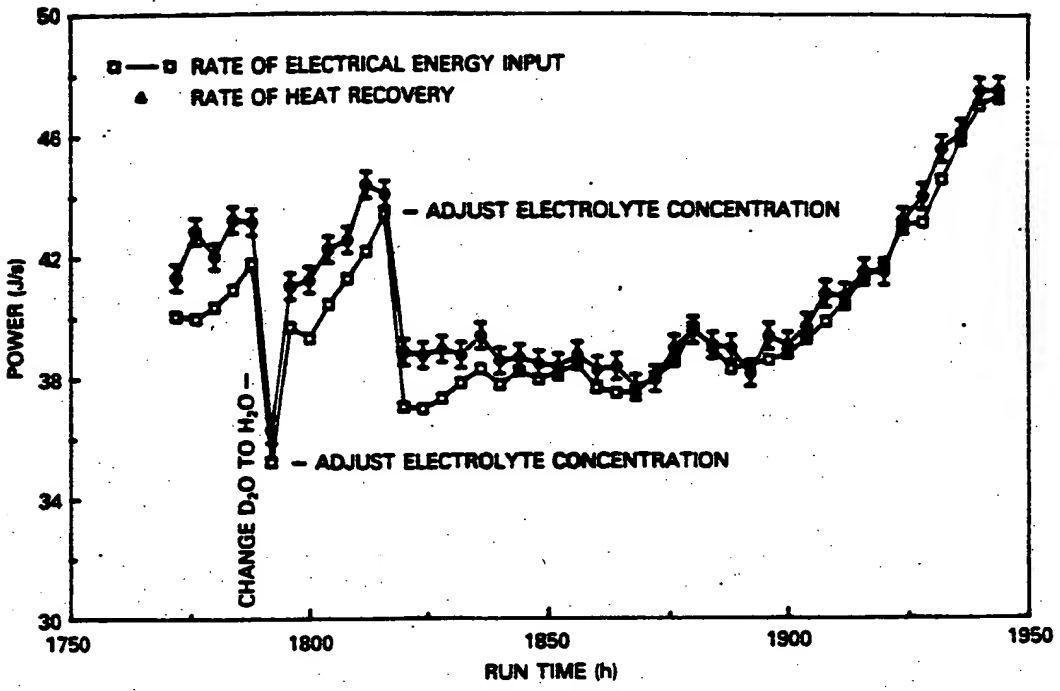

Fig. 12. Power balance in the closed-system test during the period when the electrolyte was changed to light water. Variations in the rate of energy input were primarily due to variations in the electrolyte concentration. Each point represents the mean value of 30 measurements during a 4-h interval, and the error bars represent the maximum calculated uncertainty in the experimental values based on independent calibration of temperature and flow metering systems.

TABLE I

Change of Gamma-Ray Count Rates as a Function of Run Time and Energy Level*

Detector and Energy Level (MeV)	Mean Count Rate (count/4 h)[a]		
	1088 to 1188 h	1509 to 1609 h	1948 to 2048 h
NE-213 detector			
>0.3	29 ± 2.1	43 ± 2.4	28 ± 2.5
NaI detector			
0.14 to 0.57	785 233 ± 791	792 446 ± 497	712 468 ± 510
0.58 to 1.09	192 750 ± 285	194 227 ± 150	177 009 ± 230
1.10 to 1.60	78 523 ± 168	79 169 ± 288	72 249 ± 112
1.61 to 2.11	18 562 ± 55	19 127 ± 157	17 204 ± 52
2.12 to 2.63	11 156 ± 44	10 995 ± 94	10 252 ± 30
2.64 to 3.14	3 872 ± 31	4 446 ± 80	3 805 ± 24
3.15 to 3.66	554 ± 11	568 ± 28	565 ± 10
3.67 to 4.18	463 ± 6	468 ± 25	470 ± 10
4.19 to 4.69	421 ± 8	427 ± 7	427 ± 7
4.70 to 5.20	385 ± 7	385 ± 17	395 ± 9

*The first time interval was just before the initiation of excess power for an extended period; the second interval was during the period of excess power; and the third interval was after the test had been terminated.
[a]Mean gamma-ray count rates during the time period noted with the included errors representing the 95% confidence limit on the mean values.

Tritium

Analysis of the electrolyte showed no evidence of increased tritium concentration greater than the starting material, within an accuracy of 200 Bq/ℓ.

DISCUSSION

Although periods of induced excess power were observed during the open-system test, the most significant results were

obtained during the closed-system test. Perhaps the most important feature of the closed system is that there is no need to assume that electrolysis gases do not recombine; thus, there is less inherent uncertainty in the experimental results. Spontaneous periods of excess power were observed; even more significant, however, was the demonstration that excess power could be initiated by introducing system perturbations. A decrease in the electrolyte temperature appeared to be most efficient for this effect. One of the consequences of decreasing the electrolyte temperature is an increase in the deuterium content of the cathode.[11] Therefore, it may be advantageous to work at low temperatures and high current densities when searching for deuterium-deuterium (D-D) reactions.

Of equal importance were the several periods of apparent increases in the neutron count rate. In one case, this also appeared to be spontaneous, but in two other cases they appeared to be related to system perturbations such as cathode current cycling or electrolyte temperature change. The apparent coincidence of the increase in neutron count rate with most of the extended period of excess power was of even greater interest.

The maximum increase in the fast neutron count rate, taking into account the efficiency of the detection system, was −0.23 n/s, a value that is statistically important but relatively modest. Assuming the increase is due to neutron emissions from the electrolysis experiment and assuming spherically homogeneous emissions, this value corresponds to 1.6×10^{-23} fusion/D-D pair. The detected rates are too low, by many orders of magnitude, to explain the observed energy excesses in terms of conventional D-D fusion theory.

The apparent increases in the gamma-ray count rates appeared to be coincident with increases in the neutron count rates. These gamma-ray increases were quite modest and somewhat puzzling. With low levels of increased neutrons and the very low efficiency of the gamma-ray detectors, it was not surprising that gamma rays from the neutron/proton interactions (2.2 MeV) were not observed. However, apparent increases in gamma rays at other adjacent energy levels may indicate that some type of nuclear interaction was occurring. But again, the energy balance between the excess heat observed and an assumed nuclear process differs by many orders of magnitude.

The several periods of excess power were unequivocal and could not be explained by experimental inaccuracies or artifacts. Apparent increases in the neutron and gamma-ray count rates were quite modest and perhaps could be explained by some sort of unknown variations in the background levels of the two separate monitoring systems. However, the apparent coincidence of increases in two independent detectors, and especially the coincidence with an extended period of induced excess power and the concurrent decreases when light water was added to the electrolysis system, gives more credence to the results.

The replacement of LiOD-D_2O with LiOH-H_2O resulted in an ultimate reduction of excess power and a decrease of the neutron and gamma-ray count rates to background values. These observations suggest that deuterium is a necessary component of the electrolyte for positive results; however, the length of time required for the reductions was well over 100 h. This finding could be interpreted as demonstrating that the possible interactions are bulk phenomena, which occur throughout the cathode matrix, rather than surface phenomena, which would have disappeared very rapidly after removal of the source of deuterium.

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COLD FUSION: DOES IT HAVE A FUTURE?

Look to the rising sun

by Julian Schwinger

Abstract: Dr. Julian Schwinger outlines the case against the reality of cold fusion. It is based on preconceptions inherited from experience with hot fusion. That cold fusion refers to a different regime is emphasized. The new regime is characterized by intermittency in the production of excess heat, tritium and neutrons. A scenario is sketched, based upon the hypothesis that small segments of the lattice can absorb released nuclear energy. Julian Schwinger developed the theoretical basis for quantum electrodynamics, for which he shared the 1965 Nobel Prize in Physics with Richard Feynman and Shin'ichiro Tomonaga. This lecture was given in Tokyo near December 7, 1990.

A totally unexpected phenomenon has been discovered in a certain field of science. It could have significant implications for the future of mankind, and especially for the Japanese. The overwhelming reaction of the experts in the field is rejection, based on the absence of other effects that are considered to be necessary companions of this new phenomenon.

To quote one expert: "We know a lot about what happens... We no longer have the latitude to say 'Well, some strange event occurred and generated those things.'" Nevertheless, this new possibility seems to have enough validity that one skeptic said, "It's hard to believe it. But there seems to be something to this. It should not be necessary, however, to understand the mechanism before embracing the concept. If a proven track record can be established... you have to believe it."

Reproducibility is often cited as a canon of science. And so it is, in established areas. But, early in a study of a new phenomenon that involves an ill-understood macroscopic control of a microscopic mechanism, irreproducibility is not unknown.

To which scientific field does all this refer? In view of the title of my lecture, the question may seem surprising. In fact, the object is *seismology*. The new phenomenon is the occurrence of electromagnetic effects just prior to the onset of an earthquake. The most striking event happened on October 17, 1989. An apparatus set up by a team of radio detection specialists in the Santa Cruz mountains of California received an unprecedented blast of radio power. The strong signal continued for several hours, and then stopped, to be followed by the Loma Prieta earthquake that, last year, wreaked severe damage in the San Francisco area.

As a principle, the above also applies to the phenomenon of cold fusion.

It is astonishing that there was an early precursor of the claim to have achieved cold fusion. Dated at the beginning of the Showa era, the German title of the paper is translated as "On the transformation of hydrogen into helium." At that time, neither the existence of the heavier isotopes of hydrogen, nor of the lighter isotope of helium, was recognized. If, indeed, they did produce helium, was it ^{4}He (helium-4), or was it ^{3}He (helium-3)? Incidentally, at just that time, Nishina Yoshio was at Niels Bohr's Institute in Copenhagen. One can only wonder how he reacted to the bizarre claim.

On 23 March, 1989, the University of Utah, at Salt Lake City, threw a press party. Its purpose was to establish priority for patents on a new source of energy. The impetus was supplied by what seemed to be a rival group, down the road at Provo, Utah. The patent lawyers needn't have worried. The Provo people were investigating a very weak source of neutrons, which is only of academic interest. But, science filtered by patent attorneys is no longer science. Isn't it possible to establish a track record without reference to the initial claimants?

The National Cold Fusion Institute has provided a clearing-house for reports that bear on the reality of cold fusion. As of August, 1990, 78 other groups from all over the globe have reported positive evidence, as conveyed by the detection of one or more of these indicators: Excess heat, tritium, neutrons, γ-rays, ^{3}He. The standard response to such a list is: "Yes, but what about the much larger number of failures?" Does anyone really think that the scientific judgment is like an election, in which the majority carries the day?

The characteristics that seem to be common to all successful cold fusion experiments are: (1) Intermittency—the production of heat, of tritium, of neutrons, coming in bursts, switching on and off at random. (2) Irreproducibility—seemingly identical cells vary widely in their ability to "turn on." It may not be too much of an exaggeration to say that, early in April, 1989, everyone—including those who, like myself, had to look up the meaning of enthalpy—had thrown together an electrolysis apparatus and was waiting for dividends. After a few weeks, with no reward, they quit in disgust, and denounced it all as incompetence, or fraud. Their votes are irrelevant.

Physics Nobel Laureate Julian Schwinger of UCLA, an early cold fusion theoretician and supporter.

The defense is simply stated: The circumstances of cold fusion are not those of hot fusion.

Reproducibility is often cited as a canon of science. And so it is, in established areas. But, early in a study of a new phenomenon that involves an ill-understood macroscopic control of a microscopic mechanism, irreproducibility is not unknown. That was so at the onset of microchip studies. It also appeared in the initial phase of the discovery of high-temperature superconductivity, which, by the way, is a prime example of "embracing the concept" without having "to understand the mechanism."

What is it about cold fusion that seems to enrage a substantial number of physicists? The people who have spent a lot of money on hot fusion would doubtless echo: "We know a lot about what happens. We no longer have the latitude to say, 'Well, some strange event occurred and generated those things.'" To be specific, this is how their preconceptions work: (1) In hot fusion, the union of two deuterons, to form ^{3}He and a neutron, proceeds at about the same rate as the formation of a triton and a proton. But the emission of neutrons from palladium electrodes immersed in heavy water occurs at a rate around the insignificant background level. Conclusion: No neutrons—no cold fusion. (2) The two cited reactions are the only important ones in hot fusion. There is no independent source of excess heat. Conclusion: Incompetence. (3) Given the essential absence of neutrons, what of the claims for substantial tritium production? Conclusion: Fraud. (4) At the low energy of cold fusion, the penetrability of the Coulomb barrier is so overwhelmingly small that nothing could possibly happen. Conclusion: Stupidity.

The next item of the hot-fusioneer's creed are responses to suggested cold-fusion mechanisms: (5) Very soon after March 23, 1989, it was proposed that excess heat is produced by the formation of ground state ^{4}He in the DD fusion process. Response: Where is the accompanying γ-ray of roughly 20 million electron volts? (6) Then came the recognition that excess heat might be dominated by HD, rather than the DD reaction. Heavy water unavoidably contains some fraction of a percent of light water. The fusion of a proton with a deuteron produces ^{3}He. Response: Where is the accompanying γ-ray of roughly five million electron volts? (7) The HD reaction is a source of heat and of ^{3}He, but not of neutrons or tritium. The latter must come from the DD reaction. What happens if two fusing deuterons populate, not in the ground state, but in the first excited state of ^{4}He? That excited state is unstable against decay into a triton and a proton. It is *stable*, however, for decay into a neutron and ^{3}He. Here then, is a mechanism to account for the great disparity between neutron and triton production—the ratio is about one in a hundred-million—that seems to be characteristic of cold fusion. Response: Where is the accompanying γ-ray of about four million electron volts?

So stands the indictment of cold fusion. The defense is simply stated: The circumstances of cold fusion are not those of hot fusion.

It is a standard operational procedure, in hot fusion work, to represent the reaction rate as the product of two factors: The barrier penetration probability, which involves only the Coulomb repulsion; and, the intrinsic reaction rate, which is dominated by nuclear forces. But, at the very low energy of cold fusion, one is dealing, essentially, with a single wavefunction, which does not permit such factorization. The effect of Coulomb repulsion cannot be completely isolated from the effect of the strongly attractive nuclear forces. This is a whole new ballgame. It is, so to speak, a sumo tournament restricted to the *maku-no-uchi*, indeed, to the *yokuzuna*.

The wavefunctions for a low energy proton and deuteron, and for a low energy pair of deuterons, are effectively dominated by zero relative angular momentum. They are states of even orbital parity. The intrinsic parities of all relevant particles—neutron, proton, deuteron, triton, ^{3}He, ground state, and first excited state of ^{4}He—are also positive. So, the normally dominant process of electric dipole radiation is forbidden; it requires a parity change.

If the γ-rays demanded by the hot-fusioneers are greatly suppressed, what agency does carry off the excess energy in the various reactions? One must look for something that is characteristic of cold fusion, something that does not exist in the plasma regime of hot fusion. The obvious answer is: The lattice in which the deuterium is confined.

Imagine, then, a small but macroscopic piece of the lattice absorbs the excess energy of the HD or DD reaction. Please—I beg of you—do not rise in high dudgeon to protest that this is impossible because of the great disparity between atomic and nuclear energy scales. That is a primitive reaction to what may be a very sophisticated mechanism. And do not forget the failure of theory to predict, and then to account for the phenomenon of high temperature superconductivity. I advance the idea of the lattice playing a vital role as a *hypothesis*.

Past experience dictates that I remind you that a hypothesis is not something to be proved mathematically. Rather, it is a basis for correlating data and for proposing new tests, which, by their success or failure, support or discredit the validity of the hypothesis. It is the essence of the scientific method.

Intermittency is the hallmark of cold fusion. It incorporates irreproducibility as a circumstance in which the time intervals between bursts significantly exceed the duration of the observations. Intermittency is the ultimate rebuttal to the charges of fraud in the tritium production. Externally introduced tritium maintains an essentially constant counting rate. There is no resemblance to the switching on and off of the observed bursts. Does the lattice hypothesis have a natural explanation for intermittency?

One needs information about the lattice structure of deuterided palladium. The experts say that, "We know a lot...," but that knowledge does not include what happens in the important regime of heavy deuteron loading. There is, however, a theoretical suggestion that, in the circumstance of heavy loading, a pair of new equilibrium sites comes into existence within each lattice cell. The equilibrium separation for that pair is significantly smaller than any other such distance in the cell.

It would seem that a close approach to saturation loading is then required for effective fusion to take place. but, surely, the loading of deuterium into the palladium lattice does not occur with perfect spatial uniformity.

The replacement of impartial reviewing by censorship will be the death of science.

There are fluctuations. It may happen that a microscopically large—if macroscopically small—region attains a state of such lattice uniformity that it can function collectively in absorbing the excess nuclear energy that is released in an act of fusion. And that energy can initiate a chain reaction as the vibrations of the excited ions bring them into closer proximity. So begins a burst. In the course of time, the increasing number of vacancies in the lattice will bring about a shut-down of the burst. The start-up of the next burst is an independent affair.

This scenario raises an interesting question: Would the efficacy of room temperature cold fusion be enhanced significantly by further lowering of the ambient temperature? Lower temperature would presumably decrease somewhat the probability of the initial

Cold fusion and sonoluminescence: A postscript

Physicist Julian Schwinger's keen mind continues to probe the enigma of cold fusion, which he maintains can be explained by metal atomic lattice-induced nuclear reactions. He has published his theoretical works on cold fusion in, among other journals, the *Proceedings of the National Academy of Sciences*.

Ever up to the challenge of trying to fathom the physics behind seemingly "impossible" phenomena, Schwinger has in recent years become fascinated with "sonoluminescence." Like cold fusion, sonoluminescence "should not exist," but it does. This now well-established phenomenon occurs when ultrasonic sound, beamed into a liquid, causes bubbles to oscillate stably—to expand and contract regularly—and also to emit regular pulses of light.

Since the 1930s, it has been known that under the right conditions light can emerge from so-called "cavitation" bubbles in fluids exposed to ultrasonic sound or undergoing turbulence. In 1990, a group under Professor Seth Putterman at UCLA discovered that the light from a *single* acoustically-driven bubble could come out in extremely brief pulses of 100,000 light photons—a pulse duration of less than 50 pico-seconds, about 10^{-11} seconds—this, when the oscillation period of the emitting bubble was much larger, or 10^{-4} seconds. Schwinger has drawn parallels between cold fusion and sonoluminescence in his continuing technical publication on both topics. He has also developed an impressive theory to explain sonoluminescence.

Schwinger remarks in one of his commentaries in 1991: "The mechanisms that have been suggested for cold fusion and sonoluminescence are quite different. But they both depend significantly on non-linear effects. Put in that light, the failures of naive intuition are understandable."

For our more technically inclined readers we offer the following list of Schwinger's publications in this area these past five years. *"Cold Fusion"* Magazine will publish more of Julian Schwinger's eloquence, and his perceptions of the frontiers of physics. —Gene Mallove

Works on cold fusion and sonoluminescence by Nobel Laureate Julian Schwinger

"Nuclear Energy in an Atomic Lattice." *Proceedings of the First Annual Conference on Cold Fusion, March 28-31, 1990, Salt Lake City, pp. 130-136.*

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"Nuclear Energy in an Atomic Lattice—Casual Order", Prog. Theor. Phys., *Vol. 85, No. 4, April 1991, pp. 711-712.*

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"Casimir Energy for Dielectronics: Spherical Geometry," Proceedings of the National Academy of Sciences, *Vol. 89, December 1992, pp.1118-1120.*

"Casimir Light: Pieces of the Action," Proceedings of the National Academy of Sciences, *submitted, 1993.*

"Cold Fusion Theory: A Brief History of Mine," a talk for the Fourth International Conference on Cold Fusion, Maui, December 6-9, 1993 (spoken by Eugene Mallove, in Schwinger's absence).

fusion. But, it should increase the probability of forming and maintaining the lattice structure against the destructive onslaughts of thermal agitation. Experiment must supply the answer.

I find it both amusing and tragic that the members of a panel, investigating the charge of fraud in tritium production by cold fusion, dismissed the charge as "unlikely" and "much less probable than that of inadvertent contamination or other unexplained factors in the measurement." That the "unexplained factors" might be the reality of cold fusion was not admitted. Why? Because "critics" questioned the results, saying that the tritium was not accompanied by other fusion byproducts... " It is the old story. If a significant flux of neutrons is not observed, there cannot be any tritium, even though one finds tritium with a signature that differentiates it both from external and internal contamination.

The pressure for conformity is enormous. I have experienced it in editors' rejection of submitted papers, based on venomous criticism of anonymous referees. The replacement of impartial reviewing by censorship will be the death of science.

Does cold fusion have a future? I have little hope for it in Europe and the United States—the West. It is to the East, and, specifically to Nihon, that I turn. The willingness that the Japanese have displayed, of foregoing short-term rewards for greater long-term successes, should be a key ingredient in this endeavor.

Indulge me in a fantasy, not of the future, but of the past. I should like to think that, if cold fusion had been a burning topic a few years before 1951, as well it might, Nishina would have recognized that was a subject for open-minded research—not suppression. And, in view of the physico-chemical nature of this subject, that he would have thrown all the resources of the Institute of Physical and Chemical Research into the study and development of cold fusion. Dare one hope that a dream of the past also contains a glimpse of the future?

Domo arigato gozaimasu. Thank you very much.

Professor Emeritus Julian Schwinger is a member of the Department of Physics, UCLA.

The Solid State Alters Nuclear Behavior

Radioactive decay mystery

By Christopher Tinsley

Almost any scientific or technology periodical is not ordinarily good bed-time reading. *Physics Letters A.* is no exception. Well, usually. But open the issue for January 3, 1994, and just inside the front cover is a well-written, clear paper, titled, "Reduced radioactivity of tritium in small titanium particles," written by Otto Reifenschweiler, the retired Chief Physicist of Philips Research Laboratories in The Netherlands. It just may also be one of the most important papers in 20th century physics—though it may be a big mistake. It doesn't *look* like a mistake, it *looks* like a beautiful piece of experimental science.

Essentially the paper says that if tiny crystals of titanium are allowed to absorb tritium (in the ratio of one atom to about 285 titanium atoms) then the resultant material is less radioactive than the original tritium. [Tritium is the radioactive isotope of hydrogen, which has two neutrons plus a proton in its nucleus.] Worse, if the material is heated the radioactivity drops further. No problem. The radioactivity is being shielded somehow, and when you heat a metal the tritium will be driven out. Not so, it seems. Tritium is a beta-emitter, giving off an electron when it decays to ^3He (helium-3). These electrons can form an electric current which is measurable, tiny though it is. And the X-rays produced in the decay can be measured as well.

If it looks like a duck, walks like a duck...

Accompanying the live experiment (where any tritium released by the metal is pumped out at once) is a dummy, which measures the outgassing of an identical sample. The dummy is heated in the same way, and virtually no tritium is released below 400°C.The real jaw-dropper is that although the radioactivity drops by 28% between 115°C and 160°C, and more slowly by a further 12% at 275°C. It then rises again to slightly more than its original value by the time the metal has reached 360°C. After that, the radioactivity drops as the tritium leaves the metal at about 400°C.

That is absurd, because *the nucleus is inviolate*, except to very high energies. Although radioactive decay can be hidden or shielded, it cannot be altered (to any significant extent). Obviously something is very wrong here. Anybody reading the paper will start a hunt for errors, for loopholes.

Maybe there is a loophole, but all the obvious ones have been firmly plugged. The dummy experiment shows that virtually no tritium leaves the metal below 400°C, and any that does is pumped out immediately (the heating process takes about 10 hours).

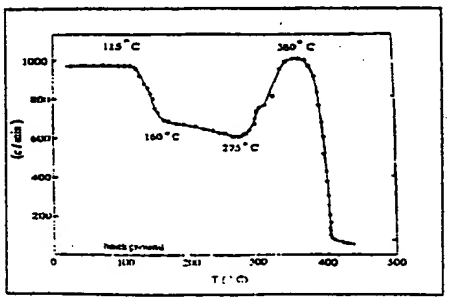
The rise in radioactivity between 275°C and 360°C shows that nothing has actually changed; the substance is giving off at least as much radiation as before. And the beta particles, the electrons, are not being diverted or hidden by some odd change in the metal. The X-rays and the current formed by the electrons are shown in a series of experiments to be in step with each other.

Perhaps a replication of this [experiment] by one of our great laboratories will be the first step to healing the ridiculous rift in science today.

"Various experiments established for both detection systems the linear relationship between the read-out and the activity."

It becomes clear from reading the paper that the author was very familiar with this material, and had done many experiments with it. This particular one was done several times, under different conditions, but with similar results. One experiment with 10 times as much tritium, and five times the rate of heating, did not show the effect.

Another, equally careful set of experiments at room temperature showed that "small accurately determined quantities of tritium" absorbed by the titanium did not emit radiation as might be expected. As more tritium was added, the emissions did not keep in step with the amount. At one point there was only half the radioactivity expected, but at double that amount of tritium the beta-decay had increased four times—back to about the expected level.



Count rate as a function of temperature in the pumped system.

The titanium used is interesting stuff. It's "a kind of soot." The titanium is vaporized in inert argon and condensed as particles, each being about 15nm in diameter. Titanium is quite a light metal and, if these particles are spherical, they will only contain about 100,000 atoms. The ball will be about 55 atoms across and have perhaps 1,000 atoms on its surface.

The question is whether tiny monocrystals are one big "grain boundary." With masterly understatement, Reifenschweiler suggests, "it seems justified to put forward a highly unorthodox hypothesis." He proposes a nuclear pair hypothesis, with pairs of tritium nuclei forming something more stable than a single one. On the face of it that sounds like an odd idea—especially since the effect is not seen with higher levels of tritium—but I have no doubt that Dr. Reifenschweiler has good reason for putting it forward.

What's in it for cold fusion?

If the effect is real, if it is confirmed, then perhaps it may be due to some interaction between the tritium and the titanium. The only (and very naive) comment I can put forward is that the neutron in deuterium is stable; in tritium it decays slowly; on its own it decays fast. Maybe that is an oversimplification, but it makes tritium look like a prime subject for some kind of process which might stabilize its neutrons. Assuming that there isn't a "trivial" explanation (Dr. Reifenschweiler is perhaps being unduly modest when he rates the chance of that at about 50%), what might be the implications for cold fusion? He makes it very clear that he has published this paper *because* of cold fusion.

It is astonishing to read that it previously existed only as an internal report within the Philips company—written in 1961! His first three references are to summaries of cold fusion progress by Storms and by Srinivasan, and the 1993 *Physics Letters A* paper of Pons and Fleischmann. And he makes suggestions for experiments which might connect his results with those of cold fusion workers.

What this paper seems to show is that solid state conditions *can modify* the behavior of atomic nuclei, which is what cold fusion scientists assert, and their opponents deny. There are none of the subtleties of electrochemistry or the complexities of "proton carrier" crystals—no calorimetry,

Cold fusion quietly takes

Cold fusion is not a big deal in Japan. In fact, it is something on the order of business as usual.

It is just an ordinary, quiet field of academic physics, like high temperature superconductivity, or X-ray lithography.

Scientists and industrialists are aware that cold fusion research is under way, and most approve of it, public opinion polls indicate. From time to time, articles about it appear in the leading scientific journals, technical magazines, and newspapers. Occasionally it makes the headlines, but press coverage is usually low-key.

Funding levels are moderate, probably around $90 million dollars per year. There is broad support for continued research from every major scientific society, and there are small groups working on the subject in most leading universities.

Most corporations working in this field probably have only five or 10 people working on cold fusion, and only a few having much larger programs.

Hideo Ikegami, one of Japan's leading cold fusion researchers, has written guest editorials in the *Asahi* newspaper, the Japanese edition of *Scientific American*, and has been quoted by the *New York Times*. When you ask him, "How are things? Is there any big news? Have there been any breakthroughs?" he always responds: "It's slow and steady. Everything is coming along normally."

Scientists are like farmers

The research is steady and uneventful. People work quietly in cluttered laboratories, spending weeks calibrating and preparing for experiments, and weeks afterwards analyzing data, and writing scientific papers. Basic scientific research usually works at this pace. The scientists are like farmers growing an apple orchard; the season is the shortest unit of time that matters to them. Most scientists think results may be years away, but Japanese scientists have made great strides in cold fusion because most of the mainstream science establishment ignores them. They get their grant money, do the research, publish their findings in the leading physics magazines, hold annual and semi-annual conferences at leading physics conferences—just like scientists in any other field.

American researchers envy their Japanese colleagues. They would love to be left alone, wishing cold fusion were treated as just another part of physics in the U.S., where the field remains a battleground of accusations and emotionalism—and research money is virtually unobtainable. Leading U.S. physics societies attack and denounce the work as criminal fraud and lunacy.

In Japan, cold fusion caused a lot of commotion in 1989, and it met very stiff skeptical opposition for a few years. After a while it slipped into the normal, quiet, calm, academic atmosphere. There are still, however, mainstream scientists who scoff at it, or ignore it, and a tiny minority which actively denounces and attacks it. The mood is open-minded, pragmatic, and patient. Most Japanese scientists are not sure yet, but they are encouraged by the results they have seen so far, and they are content to wait and see how it will turn out.

> For science, technology, business, and even the media, Japan's soil is fertile for cold fusion.

Martin Fleischmann was quoted in the UK *Sunday Times*:

"Plenty of scientists in Japan responded just as skeptically as in Britain and America. But there was a willingness to say: 'Suppose it's true, what follows from that?'"

Open minds, open doors

The Japanese as a whole are more open-minded than Americans, but they are not *much* more open-minded. It is just a small difference; they are just a little bit more willing to suspend judgment. That little slice of extra open-mindedness has allowed a little slice of careful research, at a very modest $90 million dollar per year level. If every Japanese scientist were convinced the effect is real, Japan would be spending $9 billion per year.

The cold fusion scientists themselves are completely certain of their results. They have no doubt whatsoever that the effect is real, the tritium is real, and the heat is beyond chemistry. Other scientists in Japan are only dimly aware of the results. They have not read the formal scientific papers, so they are not as certain.

There is no gigantic Manhattan Project-style cold fusion research program in Japan—and nobody has ever thought of launching one. But as the 1989 controversy gradually ebbed away, more scientists came to accept that the effect is *real*, and projects were gradually ramped up. Research is now at an all-time high.

A dramatic announcement was made on the first morning of the Fourth International Conference on Cold Fusion in Maui. December 6, 1993. Japan's Ministry of International Trade and Industry (MITI) has established a new R&D Center and a laboratory for cold fusion research with a four-year budget of $30 million dollars. Kazuaki Matsui, the Director of the Institute for Applied Energy, made the announcement. which caused quite a commotion among many Americans and Europeans. But it did not surprise many Japanese participants. Details of the plan circulated long before the conference. This announcement was the culmination of a long, slow, deliberate planning process.

Like most important projects in Japan, it was bounced around and sent out for evaluation long before it was implemented. It's clear the details were mapped out in advance: Just look at the address of the new research institute. It's one floor above the Toyota IMRA institute in Hokkaido, established two years ago. Obviously, the Japanese intend to foster close cooperation between the private industry lab on the ground floor, and the semi-private government-supported lab on the second floor.

Is the turtle winning?

Like everything else in Japanese cold fusion research, the announcement was the result of a slow, step by step, carefully planned effort. The Japanese researchers are committed to a long term effort. They are in no hurry to "crack the problem." They do not expect to find the cause of cold fusion, and win a Nobel prize next month, or next year. They say they will commit decades to the work, if that is what it takes. Noboru Oyama, of the Tokyo University of Agriculture and Technology, predicted that it might take a century for the research to pan out. Most researchers expect results before that—some say within two or three years, some say within 20 years.

Ikegami says scientists in Japan are gradually building up a mountain of essential but mundane materials science research into metal hydrides. They have come to realize that a palladium sample supersaturated with hydrogen or deuterium has many unique qualities. Palladium loaded with 50% or 60% deuterium is a relatively well-researched, well-understood metal. Palladium loaded with 90% is a brand new material—never explored before 1989—which you might say, is more hydrogen than metal at that stage.

off in Japan

BY JED ROTHWELL

An overview of scientific, political, and social attitudes toward cold fusion in Japan

American researchers envy their Japanese colleagues. They would love to be left alone, wishing cold fusion were treated as just another part of physics in the U.S., where the field remains a battleground of accusations and emotionalism—and research money is virtually unobtainable.

The Japanese are learning about surface properties, conductivity, internal structure, and about countless other properties of this strange new material. The data they have piled up is not controversial. Nobody questions the accuracy of the calorimetry, the loading measurements, or the surface analysis data itself. The data is accepted, but scientists vigorously debate what conclusions might be drawn from it.

There is no generally agreed upon theory yet to explain the data. Scientists expect that the mountain of evidence will eventually serve as the basis of a theory to explain the effect, hoping the answers will fall out of the data.

MITI's cold fusion R&D

MITI's Department of Natural Resource Development has been involved in cold fusion research for several years. They have supported low-level, small-scale research, "just enough to keep the pot boiling" as a program leader put it. Two guiding principles behind MITI's cold fusion thinking are often expressed in official statements, interviews, and discussions:

1. *The excess heat is definitely real.*
2. *If there is even a slight chance that this phenomenon might become a practical, useful form of energy, then the research must proceed.*

MITI, and private industry, are responsible for developing new technologies. That is their job. They do not see themselves as guardians of scientific truth, in the way our Department of Energy does. They don't care about scientific theories and debates. They try to avoid taking sides in the physics debates. It doesn't matter to them whether cold fusion is actual fusion, an exotic super-chemical reaction, or something else unknown to science. The Japanese look at the engineering aspects of power density, temperature, and fuel consumption. Pragmatic, results-oriented industrial planners, they resist esoteric academic debates and entanglements.

MITI appropriated $3 million dollars in 1993 for cold fusion research, money used for special equipment and other extraordinary expenses in national laboratories and universities to cover cases where normal discretionary funding was insufficient. The idea: Let the scientists go slowly and quietly, out of the spotlight. A large, lavishly-funded program might raise expectations too high, or push people to quickly produce positive results at the expense of careful science. MITI, and other Japanese R&D planners, realize that good science cannot be rushed. Research is like having a baby. Nine women cannot have one baby in one month, and nine scientists cannot do nine months of thinking and learning in one month.

In the spring of 1992, news of the MITI cold fusion R&D program began to appear in the Japanese press. On July 10, 1992 it made a big splash on the front pages of the *Yomiuri* evening edition with the bold headlines:

"Cold Fusion: Clean Energy Source to be Developed into Practical Use; Nation Begins Full Scale Research; MITI Energy Resources Div. Plans Several Hundred Million Yen Budget Next Fiscal Year [several million dollars]"

The lead paragraph said:

"The Energy Resources Department of the Ministry of International Trade and Industry, will appropriate several hundred million yen for basic research from the fiscal 1993 budget. The agency intends to spend several billion yen [several tens of millions of U.S. dollars] on the five-year project beginning in fiscal 1993. The agency has established a study group bringing together researchers, power companies, and large electric machinery producers. The group recently concluded that excess heat was indeed, generated in cold fusion experiments, although it is not sure exactly how the process works. The research is aimed at finding this out."

> Like everything else in Japanese cold fusion research, the announcement was the result of a slow, step by step, carefully planned effort. The Japanese researchers are committed to a long-term effort. They are in no hurry to crack the problem.

The MITI program director, Taizo Nakatomi, was taken aback at the commotion this raised, going to great lengths to downplay the scale and importance of the program.

A Nikkei trade publication, the *Superconductor Newsletter* quoted him:

"This is not cold fusion research per se. We are investigating the prospects for improving fuel cell performance . . . The report in the *Yomiuri* newspaper that we will begin a program to study cold fusion in the next fiscal year may cause a misunderstanding. What we are going to do is to conduct exploratory 'paper' research to determine whether or not it is possible to improve the performance of things like fuel cells and to create a new, efficient battery by utilizing the heat generated by metals that have been loaded with hydrogen isotopes . . .

"The thing we are paying attention to is the excess heat, whether the mechanism explaining that heat is nuclear or chemical is no concern of ours. For one thing, our responsibility in the Technical Division is to develop fuel cells, not nuclear fusion. Since that article about our developing cold fusion came out, we have been inundated with calls, which have become a big nuisance."

One reason Nakatomi wanted to downplay the connection with fusion is because he was engaged in a turf war with the hot fusion program at MITI. On October 17, 1992, in a report on the Third International Cold Fusion Conference in Nagoya (ICCF3), the *Yomiuri* wrote:

"[MITI's] decision to study cold fusion shocked the scientists who are researching orthodox 'hot' fusion, in MITI's Technology Research agency. It is no wonder they were surprised; under the auspices of the Nuclear Power Division, this group has been spending several trillions of yen per year to develop a gigantic hot fusion reactor, the 'JT-60.'"

The Nuclear Power Division had already performed cold fusion replication experiments for two years, and judged that cold fusion was not suitable as a source of energy. When the cold fusion program was announced, the Nuclear Power Division retaliated by declaring: "The kind of fusion energy that the nation has decided to proceed with is hot fusion. Cold fusion development is not part of this plan.

"Taking a dim view of this petty bureaucratic squabble, industry has again become excited by prospects for cold fusion. When cold fusion was first announced, the nation's large electric equipment manufacturers and others jumped into the research, and the stock prices of precious metal companies producing the palladium needed for cathodes shot up. However, that sort of response fizzled within a year. However, recently, in March, the Japanese Energy Department formed a 'New Hydrogen Energy Panel' to study cold fusion. Although the department asked that the panel be limited to only 10 companies, many more expressed interest, and the panel has now been expanded to 15 major corporations."

While this program was big news in the summer and fall of 1992, the program in fact started at least a year before that, in 1991. This is the list of consortium members in late 1992:

Chubu Electric Power
Hitachi
Toshiba
Fuji Electric
Mitsubishi
NKK
Kyushu Electric Power
Nippon Steel
Tokyo Electric Power
Tokyo Gas

Osaka Gas
NTT
Aishin (a subsidiary of Toyota)
Kepco Power
Mitsubishi Materials

In 1992 and 1993 top research directors from these corporations met from time to time to talk and share ideas about cold fusion. Some NHEP members were pursuing cold fusion research quite actively with many researchers, while others were holding back. A few research directors had their doubts about cold fusion as a source of energy, believing that a major commitment, with dozens of researchers, was premature. Their attitudes matched those in the *Trigger* public opinion survey *(see sidebar on page 86)*.

Encouraged by research results in 1992 and 1993, MITI instituted a scaled up $30 million dollar program, announced at the Fourth International Conference on Cold Fusion (ICCF4). Most NHEP members are taking part in the program, along with new participants, but a few of the original NHEP members have dropped out of the consortium.

MITI, NEDO, The Institute of Applied Energy

The cold fusion research program will be conducted by the Institute of Applied Energy, established in 1978. This complicated set of relationships were shown in the viewgraph from Matsui's ICCF4 presentation. MITI is at the top, followed by the New Energy Development Organization (NEDO), and then by the Institute of Applied Energy. NEDO will handle cooperation with foreign institutions. A steering committee within NEDO will oversee research at the Institute, which has set up two new facilities dedicated to cold fusion: the R&D center, and the NHE laboratory.

NEDO is a semi-private corporation established by MITI in 1980 to nationalize Japan's remaining coal mining industries, and carry out R&D in new forms of energy. NEDO's 1993 budget was $2.1 billion, including $725 million for R&D, and $1.4 billion for coal industry restructuring, and production of industrial alcohol. Run by the government, NEDO is an "implementing agency," with its budget appropriated by MITI. MITI's minister approves projects and financial plans, and "appoints or approves of" all NEDO officials, including its president. NEDO works closely with the private sector. Senior council members include prominent experts from the private sector, and its capital is partly comprised of private sector investments.

Quasi-governmental, quasi-private industrial organizations are common in Japan, and they are usually effective. The key to their success is that they have built-in industry support from the start. Private industry is often more careful with its investment dollars, and more realistic about the prospects for technology than the government.

Under the Japanese system, if a project cannot attract substantial financial and manpower contributions from private industry, it dies before it gets off the ground. Such projects are usually bad ideas, or boondoggles that only a bureaucrat could love. There is nothing quite like these government and private cooperative projects in U.S.; the Sematech Corporation was inspired by them.

In recent years, it has become fashionable to cite the "Japanese model" of joint government and private industry R&D. Many projects touted in Washington are supposedly based upon this model. Ironically, these projects are based on a model that went out of style a generation ago in Japan. The era of the big project dominated by the government ended when private corporations grew into world class organizations strong enough to carry out practically any project themselves. There are still joint projects, but they are smaller, more nimble, and more oriented to futuristic technology than nuts and bolts industrial planning.

> "The group recently concluded that excess heat was, indeed, generated in cold fusion experiments, although it is not sure exactly how the process works. The research is aimed at finding this out."

NEDO conducts an amazing variety of R&D programs, some having little or nothing to do with energy. In joint ventures arrangements with private industry, it has established five dazzling laboratories engaged in some of the most high tech, advanced research I have ever heard of: the Ion Engineering Center; the Research Center for the Industrial Utilization of Marine Organisms; the Japan Microgravity Center; the Japan Ultra-high Temperature Materials Research Center; and the Applied Laser Engineering Center. These labs combine many unusual high tech requirements, and no other facility in Japan can do the kinds of work they do.

Cold fusion research is just another small part of NEDO's many programs. The initial research budget is only $30 million over four years, but there is great flexibility in the budget planning; if the experiments are a great success, the budget will be increased substantially.

The R&D Center and NHE Laboratory are both being run by the Institute for Applied Energy, but they will be funded and supported in two different ways. The $30 million for the NHE laboratory will come from MITI to NEDO to the Institute to the laboratory. Five corporations will contribute research manpower: Mitsubishi, Hitachi, Toshiba, the Aishin Group, and Tanaka Kikinzoku. Researchers from these corporations will work together in the lab in joint research. The R&D Center, in Tokyo, will be supported by funds from a group of 20 corporations, the original members of the NHEP plus other utility companies. The R&D Center will fund "multiclient basic research" programs at national laboratories and universities, as well as foster cooperation with foreign institutions.

The viewgraphs and organization tables shown by Matsui at ICCF4 are a small part of the NEDO planning that went into this new venture. A superb three-page planning document (which has not yet been translated into English) lays out the plan in considerable detail. Compared to Nakatomi's hesitant, noncommittal 1992 statement, the NEDO plans are bold and direct. This is because a great deal has happened in the last two years; experimental evidence is more solid, and many lingering doubts about heat, and nuclear effects have been laid to rest.

Titled "Project to Clarify the Feasibility of New Hydrogen Energy as a Practical Source of Energy," the plan gets right to the point, laying out a set of practical goals and strategies. It begins: "The New Energy and Industrial Technology Development Organization (NEDO) has embarked upon a research and development project to determine whether the form of energy we call 'new hydrogen energy' can be made into a practical source of industrial energy. This energy occurs in the form of excess heat, apparently when heavy hydrogen is absorbed in metal lattices.

"Purpose of the research: In 1989, Professors Martin Fleischmann of Southampton University (UK) and Stanley Pons, of the University of Utah (U.S.) announced the discovery of a new phenomenon. When heavy water is electrolysized with a palladium cathode, excess heat is created. Since the announcement, this experiment was replicated by a large number of researchers, to the point where reproducibility is now close to perfection. In some cases, the excess energies have been too large to be any form of chemical energy, so it is now thought to be some heretofore undiscovered new reaction.

"This reaction produces energy at levels commensurate with a nuclear reaction, and it consumes as fuel heavy water, which is available in virtually limitless supplies. It is hoped that this will become a major new form of energy..."

NEDO's planned experiments are almost all in the mainstream of "conventional" cold fusion. The emphasis will be on the original Pons-Fleischmann style heavy water palladium electrochemical cold fusion cells. A carefully coordinated set of experiments is planned with sophisticated on-line, in-situ de-

The following speech was delivered by the late Mr. Minoru Toyoda during the Third Annual Conference on Cold Fusion banquet in Nagoya, Japan, on October 23, 1992. Born August 3, 1913, died on December 15, 1992. He was a senior member of the Toyoda family, the founders and principal owners of the Toyota Motor Company. Before his passing, he was Honorary Advisor to all of the Aisin family industries (Toyota subsidiaries), including Technova, Inc.—Eds

My name is Minoru Toyoda, and I am the Honorary Chairman of Technova, Incorporated.

I was invited by Professor Ikegami, chairman of the committee of this international conference, to the dinner tonight, but because of a slight problem with my health, the doctor has advised me to excuse myself from official functions. I sincerely regret that I will not be able to enjoy meeting and conversing with all of you. I have asked Mr. Kyotani, Chairman of Technova, to kindly read this message expressing my convictions, on my behalf.

I am delighted that the Third International Conference on Cold Fusion is being held on such a grand scale here in the city of Nagoya, Japan. I am pleased to welcome eminent cold fusion researchers from all over the world. It is my fondest hope that you will be able to exchange ideas and information in spirited, open, and productive debates.

For a long time, I have held the strong belief that equitable growth in the world economy during the 21st century will only be achieved by the harmonious development of science and technology, through international cooperation.

To make this belief a reality, I established Technova in Tokyo in May 1978, as an organization that would have complete freedom to participate in the international forum of research. During the 14 years since its inception, in the ever-changing world of international research, we have made steady progress, thanks to the help of some of the best minds in the world.

Technova has been very active in the development and application of advanced technology, and in adapting advanced technology to practical uses. We have also actively promoted the international interchange of technology and ideas. Technova's staff and advisors have made continuous progress, leaving their mark both nationally and internationally.

I recall that in June 1982, at the Eighth Annual Summit of Developed Nations in Paris, French President Mitterand stressed the necessity for cooperation between science and technology. I examined future trends, and envisioned an ever-growing need for progress through the promotion of science and technology. With the cooperation of my many friends from beyond our borders, in July 1985 I established IMRA Europe, an international research and development laboratory located in Sophia Antipolis, a research park in the suburbs of Nice, France. The laboratory began operations in June 1988, and has been actively involved in advanced research, mainly in the field of energy.

When I established IMRA Europe, I had a vision, world-wide in focus, to set up a global structure for the development of future technology. I named this project the "IMRA Plan." It had its research base in Japan, Europe, the U.S., and Asia under the same name IMRA.

Its purpose was to network these four regions together in order to make more efficient use of human resources by exchanging people and ideas, while winning the world's confidence to achieve our goals. This plan progressed steadily, and now IMRA Japan, IMRA Europe, and IMRA America have already begun work. Today, we are planning the establishment of IMRA Asia.

tectors for helium, tritium, and other particles. Also in the works are extensive materials sciences studies of cathode material.

The technical goals NEDO hopes to accomplish during the three-year schedule are in two categories: work with the excess heat phenomenon; and materials science, but *excess heat* is their main focus. Scientists hope to improve reproducability, measure reaction products, like helium and tritium, and identify and quantify control factors such as loading and temperature.

These issues have been the main focus of cold fusion research from the beginning—particularly mainstream research at places like SRI and IMRA. A great deal of progress has already been made in these areas, and NEDO will continue to build on this progress and finish the job.

Some people find the pace of research planned by NEDO a little too slow, and the choice of research topics a little too conservative and safe. Perhaps this is so, but on the other hand it is hard to argue with success. The Japanese approach has yielded slow but steady progress, and a gigantic data base of information about metal hydrides.

Electrochemist and cold fusion pioneer Hadahiko Mizuno of Hokkaido University visited the newly established NEDO labs in January, reporting that 12 palladium heavy water cells are up and running, six open, and six in closed-cell configurations. The experiments use conventional, "safe", old approaches, but Mizuno expects the program will include leading edge approaches, like his own work in ceramic material proton conductors.

NEDO's other activities include: research support in the national laboratories, both laboratory work and theoretical studies; establishment of a database of scientific papers and information on cold fusion; coordination with overseas institutions, particularly EPRI; promotion of the exchange of personnel and information.

What's in a name?

One term was conspicuously missing from Matsui's ICCF4 presentation, and it's also a term nowhere to be found in NEDO's planning documents either—in English or in Japanese. It is those two little words, "cold fusion" (in Japanese, "jyouon kukuyuugou"). MITI banned that term from its official vocabulary, rather calling the effect NHE: "New Hydrogen Energy" (in Japanese, "shin suisou enerugii").

MITI adopted "new hydrogen energy" for several reasons. It represents a fresh start, and avoids any controversy surrounding the term "cold fusion." NHE is a neutral term fitting whatever form of energy this actually is.

Many American and European scientists, including Hagelstein of MIT, and Storms, of Los Alamos National Laboratory, have also advocated a name change for these same reasons. Also, I suppose, the NHE planners are hoping the neutral term "NHE" will help in the turf war within MITI. They are declaring, in effect, that they are not competing with hot fusion because this is *not* "fusion," it's New Hydrogen Energy.

While the term they use is different, there can be no doubt that the effect MITI and NEDO refer to is what the rest of us call "cold fusion." The NEDO planning document makes this clear. Right up front they refer to the effect Pons and Fleischmann discovered, and announced in 1989, which is most easily recognized and characterized by massive excess heat far beyond the limits of chemistry.

Mainstream support; private industry research

There is no question cold fusion research enjoys quiet support from mainstream physics societies in Japan, that many corporations are working in the field, and that many others are interested in it. ICCF3's sponsor and attendance list proves that. [See attached list.] Support did not start in 1992, either. In September 1991, I called the Atomic Energy Society a few weeks before their annual conference, asking for the agenda for the fusion meetings. The secretary asked, "hot or cold?" I received agendas for both, but naturally,there were more hot fusion papers scheduled than cold fusion. There was a half-day cold fusion session, with 10 presentations. No comparable U.S. physics society would allow even one paper.

Editors at major Japanese science journals

'Cold fusion is not just something to be studied by a single enterprise or a single nation. I am confident it will become a precious asset to all mankind, as the ultimate, ideal form of energy, so it should be shared among all the nations of the earth.'

Thus, I have enthusiastically put my heart into promoting the development of future technology. At the same time, I have always felt anxious about the issue of alternative energy. The dire need to replace drained petroleum resources is a stark warning for the 21st century.

I felt strongly concerned in March 1989, when Dr. Fleischmann and Dr. Pons announced the cold fusion phenomena. Fortunately, I found an opportunity to invite both professors to Japan, where we became good friends. After close conversations with them, I became even more firmly convinced of the importance of cold fusion.

Later, when Technova received a joint research proposal from Professors Fleischmann and Pons, I was determined to do eveything I could to offer them an opportunity to work to their hearts' content, and allow them to become totally engrossed in the research. It was my judgment that IMRA Europe in Nice would be the ideal environment for them. So I offered this facility, and now they are giving their undivided attention to advancing their research there.

Furthermore, in July [1992], to advance cold fusion research more effectively, we opened IMRA Japan in the New Sapporo Technology Park, Hokkaido. With the cooperation of various experts, we are working on cold fusion right here in Japan.

To assure the success of a technology, obviously, there must be support from a wide variety of scientific fields. In other words, the harmonious development of science and technology is precisely the right way to achieve valuable results which can contribute to mankind. The reason we support cold fusion research actively is because, as a business enterprise, we feel we must contribute more to science.

Cold fusion is not just something to be studied by a single enterprise or a single nation. I am confident it will become a precious asset to all mankind, as the ultimate, ideal form of energy, so it should be shared among all the nations of the earth.

Therefore, this is my hope, and my message to you, the cold fusion researchers: Please continue to work with all your might to make this new form of energy a reality, because you offer such hope to the coming generations of the 21st century. You will help them fulfill their greatest dreams and ambitions for the future. Thank you for your attention.

take cold fusion seriously, regularly publishing papers on the topic. A good source of scientific papers is the Ministry of Education's *Jouon Kakuyuugou No Sougou Kenkyuu*, Government Publication No. 02305015, 359 pages, edited by H. Ikegami. A collection of reprinted papers from 1990 and 1991, it is mostly in Japanese, with some papers in English.

One of Japan's leading scientific journals is *Oyou Butsuri* (The Japanese Journal of Applied Physics). It has published articles about cold fusion, starting in November, 1989. The July 1993 issue, Vol 62, No. 7, ran six articles about cold fusion. A scientist outside the field told me, "this looks like semi-official recognition and acceptance to me." It is semi-official recognition because support from the mainstream physics societies is not always unanimous or whole-hearted. There are still factions strongly opposing cold fusion. They complain, and campaign against funding research, as reflected in the Nakatomi statement and in the *Yomiuri* article quoted above. The *Yomiuri* ridiculed the opponents, describing hot fusion scientists' attempts to stop cold fusion as "petty bureaucratic squabbling."

A cold awakening?

The fact that cold fusion threatens to put hot fusion out of business is not lost on anyone. Ikegami, one of the world's leading hot fusion scientists, is a professor at the National Institute for Fusion Science (NIFS), which is slated to become the home of Japan's next generation tokamak hot fusion reactor. In a June, 1992 article in *Aera* magazine, science journalist Atsuko Tsuji quoted Ikegami: "Officially, we aren't supposed to study cold fusion..." She pointed out:

"The National Institute is pushing a plan to spend nearly 100 billion yen [$900 million] to build a plasma fusion machine. If it were possible to create a fusion reaction on a budget only one thousandth of that, the very existence of the National Institute would be called into question."

Opposition is still active, but it is increasingly ineffective. Many of the scientists expressing exasperation or contempt for cold fusion are high energy particle physicists, who feel they are the creme de la creme of physics, and who deeply resent electrochemists and nuclear engineers declaring that a scientific revolution is under way in the low energy domain. They do not oppose cold fusion so much as they ignore it—give it the cold shoulder.

Occasionally, bitter, unethical opponents surface, trying the same dirty tricks that worked so well in the U.S., such as innuendo, ad hominem personal attacks, distortion, and so on—tactics more common in the early days in 1989 and 1990. Usually, the fight is conducted quietly, but twice in 1993 it broke out into the open: once in a strange NHK television science documentary, and once in a venomous, anonymous attack on cold fusion in the *Applied Physics Society Letters*. Fortunately, this kind of opposition is becoming rare in Japan.

The cold fusion arena

The big questions Americans always ask are: How many people are working on cold fusion in Japan? How much are they spending? How many companies are working on it?

My answers are honest, but disappointing: Nobody knows.

There is no way to tell. We can only estimate by counting the number of conference attendees, and those publishing papers, or filing patents, giving a rough count of 600 people working full-time on cold fusion. Multiply 600 by the average salary, overhead, and equipment costs and you get a total annual R&D budget of roughly $90 million, not counting major one-time capital expenditures like the construction of the Toyota IMRA laboratories in Hokkaido and Nice, France.

At the Second International Conference on Cold Fusion (ICCF2) in June 1991, in Como, Italy, Ikegami said:

"There are more than 100 scientists at present working on cold fusion in Japan, spanning more than 40 universities and institutions. They are organized into about 20

Nagoya conference attendees

Statistics from the Third International Conference on Cold Fusion: The "Nagoya Conference". The data was compiled from "Frontiers of Cold Fusion", Proc. 3rd Int. Conf. Cold Fusion, Nagoya, 1992, ed. H. Ikegami (Universal Academy Press, Tokyo, 1993), p. iii and p. 681.

Total number of Nagoya conference participants: 324

Participation by Country: Canada 2, China 11, France 5, Germany 2, India 1, Italy 20, Japan 203, Korea 1, ROC 4, Russia 12, Spain 2, Switzerland 2, UK 2, Ukraine 2, U.S. 55.

The Nagoya conference was sponsored by seven prestigious Japanese scientific societies:

The Physical Society of Japan
The Japan Society of Applied Physics
Atomic Energy Society of Japan
The Institute of Electrical Engineers of Japan
The Chemical Society of Japan
The Electrochemical Society of Japan
The Japan Society of Plasma Science and Nuclear Fusion Research

Additional sponsors included:

Aichi Prefectural Government, Aisin AW Co., Ltd., Aisin Seiki Co., Ltd., Central Research Institute of Electric Power Industry, Daido Steel Co., Ltd., Digital Equipment Corporation, Canon, Japan Godo Steel Ltd., Kubota Corporation, Kyoei Steel Ltd., Mitsubishi, Materials Corporation, Mitsubishi Research Institute, Inc., Mitsubishi Steel Mfg. Co., Ltd., Nagoya City Hall, Nakatomi Satoshi, Niki Glass Co., Ltd., Nippon Steel Corporation, NKK Corporation, Nuclear Fuel Industries, Ltd., Ohyo Koken Kogyo Co., Ltd., Osaka Gas Co., Ltd., R-DEC Co., Ltd., Seiko EG&G Co., Ltd., Sumitomo Metal Industries, Ltd., Tanaka Kikinzoku Kogyo K.K., The Federation of Electric Power Companies, The Japan Steel Works, Ltd., The Tokyo Club Toho, Sanso Co. Ltd, Tokyo Gas Co. Ltd., Toshiba Corporation, and ULVAC Japan Ltd.

The conference was dominated by Japanese participation. More than 203 Japanese scientists, engineers, and industrialists attended. Well-known and little-known Japanese companies attended:

Air Liquide Lab, Aisin Newhard Co., Ltd., Aisin AW Co., Aisin Seiki Co., Ltd., Asahi Glass Company, Chlorine Engineers Corporation, Chubu Electric Power Company, Cogema, Japan, Daikin Industries, Ltd., Electrotechnical Laboratory, Equos Research Co., Ltd., Fuji Electric Hitachi, Ltd., (Nuclear Power Systems Division), Honda R&D Company, Horiba, Ltd., IMRA Japan, IMRA Material R&D Co., Japan Development Bank, JGC Corporation (Nuclear Advanced Technology Division), Kansai Electric Power Co., Inc., Mitsubishi Atomic Power Industries, Inc., Mitsubishi Heavy Industries, Ltd., Mitsubishi Materials Corporation Mitsubishi Research Institute, N.E. Chemcat Corporation, Nippon Steel Corporation, NKK Co.

Also, NTT Basic Research Laboratories, NTT LSI Laboratories Nuclear Fuel Industries, Ltd., Nuclear Engineering, Ltd., Osaka Gas Company, Owners Engineers Co., Permelec Electrode Ltd., Power Reactor and Nuclear Fuel Development Corporation, Sanyo Research Corporation, Sumitomo Chemical Co., Ltd., Sumitomo Electric Industries, Ltd., Sumitomo Metal Mining Co., Ltd., Tanaka Precious Metals, Technova, Inc., Tokyo Electric Power Company, Tokyo Gas, Toshiba Corporation, Toyota Central Research and Development Labs, Toyota Motor Company, and Yokogawa Electric Corporation.

A large number of Japanese universities were represented, including: Aoyama Gakuin University, Chubu University, Chuo University, Ehime University, Hiroshima Institute of Technology, Hokkaido University, Iwate University, Kinki University, Kyoto University, Kyushu University.

Also, Meiji University, Musashi Institute of Technology, Nagoya University, Nagoya University (Plasma Science Center), Nippon Bunri University, Osaka Institute of Technology, Osaka University, Osaka City University, Ritsumeikan University, Shizuoka University, Tohoku University (Cyclotron and Radioisotope Center), Tohoku University (Institute for Materials Research), Tohoku University (Laboratory for Nuclear Science), Tokai University, Tokyo Institute of Technology, Tokyo Metropolitan University, Tokyo National College of Technology, Tokyo University of Agriculture and Technology, Tsukuba University, University of Osaka, Prefecture University of Tokyo (Meson Science Laboratory), University of Tokyo (Dept. of Nuclear Engineering), Utsunomiya University, Waseda University, Yokohama National University.

Other Japanese Institutions and Agencies represented were: Asian Office of Aerospace Research and Development, Biological and Agricultural Research Institute, Central Research Institute of the Electric Power Industry, Institute of Applied Energy, Japan Atomic Energy Research Institute MITI (Electric Power Technology Division), National Institute for Fusion Science, National Laboratory for High Energy Physics, New Energy & Industrial Technology Development Organization, Nomura Research Institute, Ltd., (Investment Research Dept.), Osaka Science and Technology Center,

The Institute of Physical and Chemical Research, Tokushima Research Center.

Fifteen of the corporations are members of the Ministry of International Trade and Industry's cold fusion R&D consortium. They are: Chubu Electric Power, Hitachi, Toshiba, Fuji Electric, Mitsubishi, NKK, Kyushu Electric Power Nippon Steel, Tokyo Electric Power, Tokyo Gas, Osaka Gas, NTT, Aisin Seiki (a subsidiary of Toyota), Kepco Power, and Mitsubishi Materials.

research groups which collaborate to carry out the experiments. Only three groups, Yokohama National University, Tokyo University of Agriculture and Technology, and IMRA Japan, are working exclusively on excess heat, while the others mostly study fusion products (neutrons and charged particles such as tritium, protons, and helium-3)."

There are about six times more scientists in the field now than in 1991. Most of the increase is in private industry, rather than government national laboratories and universities. There is no way to gauge the precise extent of academic funding for cold fusion in Japan because most of the work is done by professors in national universities. There is no central accounting for them, and no central control over their research activities. They are independent. They have tenure, and they have the use of fully-equipped laboratories. If they can interest a graduate student or two, they can get plenty of enthusiastic help.

Full professors get $45,000 yearly in discretionary funds to buy whatever equipment they want. Akito Takahashi, of Osaka National University, jokingly referred to this amount as "sparrow tears," but $45,000 can go a long way in a cold fusion experiment when one already has a fully-equipped lab. MITI provides grants for cold fusion research at national laboratories to cover the cost of special equipment and other expenses that exceed discretionary fund levels.

There weren't quite as many Japanese companies represented at Maui in 1993 as there were in Nagoya, geographical distance being the main reason. Also, some of the Nagoya attendees only came to satisfy their curiosity. Some were not performing research in this field—they were just curious. In 1983, Ikegami guessed that about 20 companies are seriously working in this field. But a "serious" cold fusion project takes many millions of dollars.

Perhaps there are only 20 big companies

with multimillion dollar projects underway, perhaps more. As far as is known, IMRA is the only Japanese company with two dedicated cold fusion labs and dozens of scientists working in the field, but there could be 10, 20, or 30 other companies with dedicated labs. No one has any real way of knowing. Corporations aren't in the habit of divulging information about important, competitive R&D efforts. Most such research remains secret until patents are granted, or finished products are revealed.

Judging from corporations' published papers, patents filed, and representatives at conferences, it's safe to estimate there are some 450 people working on cold fusion in private industry. Suffice it to say there is significant research going on behind closed doors.

The clarion call to science

Hideo Ikegami's introduction to the Third Annual Conference Proceedings on cold fusion reflects the deep-seated hope that drives scientists to work in this field—year after year, in spite of the immense difficulties.

"At the conference, the video produced by Drs. Fleischmann and Pons allowed us to see that a controllable excess heat generator was already at hand. These remarkable efforts were confirmed thanks to the efforts of Dr. McKubre, Dr. Takahashi, Dr. Kunimatsu, and Dr. Storms, who along with Drs. Fleischmann and Pons, reported on their work at the conference and offered extensive documentation of their experiments.

"It is my belief that cold fusion will become one of the most important subjects in science," Ikegami continued, "one for which we have been working so patiently, with dedication and courage, for future generations..."

What really drives scientists, though, is not an urge to help future generations. They conduct frustrating, difficult experiments year after year because it's fun. It is what Oppenheimer called "a sweet problem."

Makoto Okamoto, of the Tokyo Institute of Technology, worked for a solid year with no results. Just as he was thinking of quitting, he finally got several positive neutron detections in succession. Atsuko Tsuji quotes him:

"You might call it a miracle. Once you have seen it happen, everyone in the lab becomes fascinated by the phenomenon, and you can't give it up. You can't let go."

Popular press coverage; the occasional big splash

News of cold fusion does not appear in the popular Japanese newspapers and magazines every day. Far from it. There are probably two or three dozen articles a year about it, ranging from a paragraph or two, to in-depth interviews with leading scientists in the field.

Japan witnessed a burst of excitement over cold fusion in 1989, similar to that seen in the U.S. and Europe, followed by angry debate. Japanese cold fusion scientists who have been in it from the beginning, like Mizuno, say the situation was not at all pleasant, but didn't begin to compare to the emotional flood in the U.S.

Articles tend to come in spates, after a conference, or after some breakthrough is announced. Sometimes, the breakthrough is more in the minds of the journalists than the scientists. Scientists usually take a year or two to decide whether an experimental result really is an important breakthrough. Newspapers look for quick resolutions of the issues. They want to know who is winning, who is losing, what's hot, and what's not. Periodically, they "rediscover" the field with renewed enthusiasm, apparently hoping for a return of the 1989 fever—the last thing any scientist in the field wants to see. In March 1992, headlines in a *Yomiuri* article speculated:

"Low temperature fusion: Will it boom again? *Lack of neutrons, the mystery deepens.*"

It's safe to say that scientists generally hope the cold fusion field doesn't "boom" again the way it did in 1989.

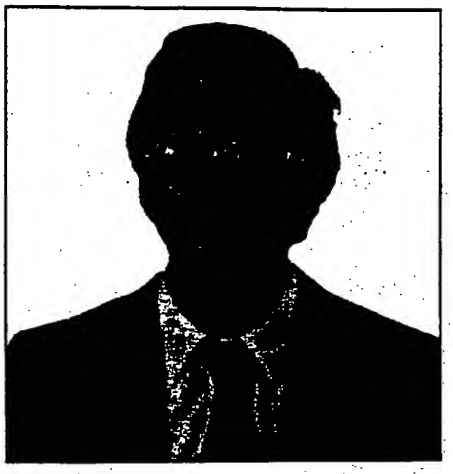
The best in-depth technical articles for the general reader appear in *Trigger*. The March 1993 edition, Vol. 12, No. 3 banners on the cover: "A special edition on the Cold Fusion Revolution," and includes six excellent articles. The May 1993 edition, Vol. 12, No. 6 ran a three-page article describing the special meeting of the Electrochemical Society, in March 1993, devoted to cold fusion. Some good technical articles and notes have appeared in the Japanese edition of *Scientific American*.

Well-written technical articles geared for the general reader have appeared from time to time in every major Japanese newspaper, and in many different magazines, including Japan's leading monthly *Bungei Shunju*, the *Asahi* weekly magazine *Aera*, the Japanese edition of *Playboy*, and many others.

Cold fusion scientists sometimes write articles for magazines or newspaper columns, and they are often interviewed. A good case in point was *Bart* magazine, which published a three-page interview with Dr. Eugene Mallove in its April 1993 issue.

Most popular books and articles about cold fusion in Japan are neutral or positive. Authors usually accept as fact that the heat is real—and beyond the limits of chemistry. A few articles, however, still question the reality of the effect. The only extremist, negative book yet published in Japan is a translation of Gary Taubes' book *Bad Science*. It was reviewed in the January 1994 *Yomiuri* by Mitsuhiko Tanaka, who seems puzzled by it.

Tanaka naively asks why Pons and Fleischmann were not interviewed in the book, and says, "If the descriptions of the research in this book really are accurate, the scientists are not the only ones who should be roundly criticized..." At least Tanaka leaves the question open; he has some doubt about the veracity of the reporting. It's pretty well accepted that almost every U.S. reviewer fell for Taubes' story, hook, line and sinker.



Jed Rothwell

The weekly science page in the *Yomiuri* newspaper is fun to read. Editors, opinion makers, and ordinary people gung-ho about the future in Japan tend to enjoy technology. *Yomiuri* talks about the latest gadgets and discoveries, matters of a practical nature, such as promising new medical treatments, earthquake prediction, or advances in fiber optics and how they will contribute to the information highway.

This is quite a contrast to the *New York Times* weekly *Science Times* page, which features obscure articles about evolution, bizarre, esoteric articles about "string theories," and catastrophic, end-of-the world predictions about gigantic meteorite strikes in the earth's atmosphere.

The Japanese press *never* declares that cold fusion is a sure thing. It never trumpets cold fusion as a panacea. I have not seen one article predict that cold fusion will replace all other forms of energy. But, year after year, factual, low-key articles in newspapers, news magazines, and science magazines present the facts about cold fusion breakthroughs.

Newspapers cautiously endorse the research, saying it is definitely worth pursuing, at careful, low levels of funding. The press acknowledges that it might become a practical source of energy. That prospect is never far from anyone's mind, so the press strongly advocates more research to get to the bottom of it.

Some leading science magazines are more enthusiastic about cold fusion than the newspapers, particularly *Trigger*, whose April 1993 cover boldly declared: "The Cold Fusion Revolution is Here!" and ran six in-depth articles. Three articles appeared in the June issue, all excellent, factual, businesslike, and pragmatic.

The revolution is in physics and science. *Trigger's* editorial stance is that cold fusion is a proven, nuclear reaction, but makes no predictions that cold fusion will be a practical source of energy. Like the rest of the Japanese press, *Trigger* has adopted a wait and see attitude.

For science, technology, business, and even the media, Japan's soil is fertile for cold fusion.

The Fourth International

Report from Maui

By the sea at Maui—cold fusion conferences as far as the eye could see. The International Conferences on Cold Fusion have become milestones in a rapidly expanding field. The Fourth International Conference on Cold Fusion (ICCF4), held on Maui, December 6-9, 1993, did not disappoint. At the very beautiful Hyatt Regency in Lahaina, dozens of researchers announced landmark and breakthrough results. How fitting this time to have a cold fusion conference on a beautiful island surrounded by the fuel of the future.

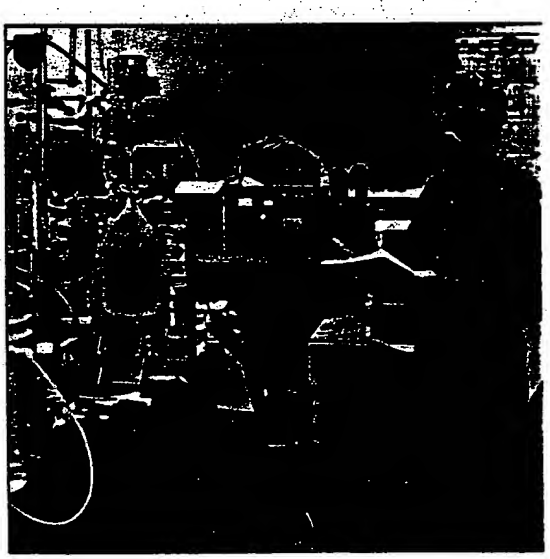
In the background of Maui were sweet and bitter memories of earlier cold fusion conferences. One year after the March 23, 1989, cold fusion announcement, the First Annual Conference on Cold Fusion convened in Salt Lake City amid loud controversy. *Nature* magazine sent no reporter, but still felt free to attack the conference in its editorials. Robert Park of the American Physical Society on national television called that meeting a "seance of true believers."

The more serene Second International Conference on Cold Fusion (ICCF2) was held in Como, Italy, June—July, 1991. Nagoya, Japan, was the venue of ICCF3 in late October 1992, which had the full support of the Japanese scientific establishment. The Maui conference was sponsored by the U.S. Electric Power Research Institute (EPRI) of Palo Alto, California, the research arm of the American electric utility industry, which continues to fund cold fusion research at SRI International and elsewhere.

Future cold fusion conferences will continue the custom of following a rotation: U.S., Europe, and Asia. At the conclusion of the Maui conference, the Organizing Committee announced that ICCF5 will be held in the spring of 1995 in Nice, France, and ICCF6 in Beijing, China, thus fulfilling the strong wishes of the Chinese researchers and government to host a cold fusion conference.

The four-day conference consisted of morning plenary sessions— each with five or six speakers. The afternoons featured for the first time *parallel* sessions, e.g. one session devoted to calorimetry, one to theory, one to nuclear effects, and one to materials, in various combinations for the different days. A measure of how mature the cold fusion field has become is that it required parallel specialist sessions. Thus, it became impossible, for the first time, for one person to take in everything. The scope of the conference encompassed almost 300 participants, and more than 150 technical paper presentations. A technical poster room was open throughout the conference. On the afternoon of the closing day, a panel session of participants summed up ICCF4.

Since it is obviously impossible in a very short space to relate all that took place at the conference, this is a modest attempt to recall some of the most significant findings and events. To illustrate the depth and breadth of activities, we have appended the pre-conference listing of papers, which was necessarily incomplete. Also, Professor Robert A. Huggins of the Department of Materials Science at Stanford University, an early pioneer in the cold fusion field, has graciously provided *"Cold Fusion"* Magazine with his impressions of ICCF4, which we reprint after this overview of ICCF4 highlights. Professor Huggins writes of the conference from the special viewpoint of a materials scientist.



Roger Stringham, visiting at Los Alamos National Laboratory in 1993, conducts a "microfusion" experiment with the E-Quest device.

Japan's New Hydrogen Energy (NHE) Research Program

During the first morning session, Dr. K. Matsui, director of the R&D Center for New Hydrogen Energy in the Institute of Applied Energy in Tokyo, announced that the NHE program would be launched to "clarify the feasibility of NHE as one of the future energy sources." The period of the project: November 1993—March 1997. The budget: $30 million dollars for four years. [This is a budget request, for which confidence exists that it will be granted.] Leading industries are involved: Ten (10) electric utilities, plus Tokyo Gas, Mitsubishi Heavy industries, Hitachi, Toshiba, Nippon Steel, Aishin Group (Toyota), Tanaka Kikinzoku, NTT, IHI, and NFI. The organizational chart shows that MITI will provide the research funding to the New Energy Development Organization (NEDO), which will have under it the Institute of Applied Energy—the R&D center for the NHE project based in Tokyo and the NHE Laboratory in Sapporo. Cooperation with EPRI and SRI International in the U.S. is explicitly provided for.

Cold fusion with solid state devices

One of the most startling developments at ICCF4, one which has already captured the attention of the Japanese press, was that the cold fusion effect can be produced at a high level in a solid ceramic material, such as a strontium-cerium-oxide "proton conductor." These materials are similar to high-temperature superconductors. Professor T. Mizuno and his group at Hokkaido University have tested these "solid electrolyte" plates maintained at 300 to 400°C. Excess heat on the order of 100 watts per square centimeter emerged during absorption-desorption cycles of deuterium-containing hydrogen gas under the application of an alternating elec-

Conference on Cold Fusion

BY EUGENE F. MALLOVE

tric field. Excess heat amounting to 50 watts for some 20 hours was achieved. The input electric power was tiny—about 7.2 x 10^{-4} watts. The power ratio was thus a huge 70,000. This device was only 0.8 cm in diameter and 0.1 cm thick.

True, the Mizuno solid-state device requires elevated temperatures of a few hundred degrees C for the excess power to emerge, provided in this experiment by a separate electrical resistance heater. In a practical implementation, the reaction chamber would be well-insulated so that the energy of the reaction would self-heat the ceramic, unlike in Mizuno's experimental apparatus where heat transfer to the environment was large.

Independently of Mizuno et al, Jean-Paul Bibérian of R&D International, Orinda, California, had a poster display on his "Solid State Cold Fusion" device made of $AlLaO_3$, aluminum lanthanum oxide. He, too, has observed what appears to be copious excess heat evolution in a deuterium atmosphere. It appears that he is able to achieve 500 watts/cm³ from his small wafer crystals, with a total output power of tens to a few hundred watts. The excess heat is highly reproducible. The originator of this work, according to Bibérian, was F. Forrat in France, who took out French patents in 1989 and 1990.

Confirmation of excess heat in ordinary water

The Indian group at the Bhabha Atomic Research Center (BARC) brilliantly confirmed its earlier series of tests with ordinary water. They continue to get excess heat and, in many cases, tritium above background level. They have even made a serendipitous discovery: that stainless steel poisons the process and prevents excess heat evolution. The group studied different types of nickel. Out of a series of 28 cells, 14 showed excess heat. Excess power in these cells was in the range 0.2 to 0.7 watt.

The BARC group has used off-the-shelf consumer "thermos bottles" to conduct its experiments. The thermal characteristics of the standard internally aluminized thermos bottles is typically 20-35°C temperature differential (between inside and ambient) per watt of input power (i.e., 20-35°C/watt). The group now reports a simple technique of de-aluminizing the thermos bottles with nitric acid. This allows the cells to reach steady state temperature within 10 hours instead of the 24 hours required earlier; the calibration constant now is 7-10°C/watt.

Dr. Srinivasan told this author that almost everyone at BARC now accepts the reality of cold fusion. He is planning eventually to put together a "kit" that will allow any experimenter to observe the cold fusion excess heat effect in light water—with >90% confidence. Dr. Srinivasan currently is on leave from BARC and is working at SRI International to help that group perform ordinary water-nickel experiments.

Electrochemist Dr. Reiko Notoya of Hokkaido University also has achieved excess heat in ordinary water, and like the BARC researchers, finds tritium above background level.

The team of Professors Robert Bush and Robert Eagleton of California Polytechnic University continues to report excess heat results in electrolysis with light water and potassium carbonate, as well as sodium carbonate electrolyte. The excess heat found in sodium-carbonate cells—a finding also of the BARC group—runs contrary to the claim of Dr. Randell Mills of HydroCatalysis Power Corporation in Lancaster, Pennsylvania, that no such excess is found in sodium carbonate solution, one of the requirements of Dr. Mills' electrocatalytic ("shrunken" hydrogen atom) theory for explaining excess heat.

Bush and Eagleton performed experiments in special "de-deuterated" light water having only 1% of the normal trace heavy water content. These tests, they say, prove there is a "genuine light water excess heat effect," because the de-deuterated light water cells gave the same order of excess heat as the ordinary light water cells.

The most remarkable claim of Bush and Eagleton is a seemingly definitive experiment demonstrating that rubidium (from rubidium carbonate electrolyte) transmutes into strontium during excess heat experiments. Examination of the strontium isotopes in the solution showed "statistically-significant enhancements in the ratio of $^{86}S_r$ to $^{88}S_r$ relative to the natural abundance ratio," i.e., by 325 standard deviations. The claim is that this rules out contamination from possible natural sources of strontium.

Heat After death

This follows work reported in Pons' and Fleischmann's May 3, 1993 *Physics Letters A* paper on heavy water cells that go to boiling, boil away virtually all of the heavy water, and then remain at 100°C for three hours without electric current input. This high temperature in the open dewar cell—caused by an electrode obviously hotter than the 100°C of the vapor in the cell—has been found to occur for much longer periods, for 40 hours or more. Other work reported at the conference (or hinted at as "work in progress") suggests that various materials, including special types of ceramics in deuterium atmospheres, can remain hot for long periods with minimal or absolutely no current input. This remarkable phenomenon of "heat after death," i.e., infinite power ratio, may well become a primary direction in a variety of cold fusion systems.

Triggering cold fusion by radio frequency stimulation and magnetic fields

Drs. John Bockris, Dennis Letts, and Dennis Cravens separately discussed the astonishing new finding, discovered by Dennis Letts, that radiofrequency stimulation (RF) in the MHz range (around 82, 365, and 533 MHz) produces excess heat in electrochemical cold fusion experiments. In particular, RF stimulation must be applied at precise frequencies to bring about the effect, and the effect typically occurs within 30 minutes of imposition of the RF. The power levels of RF imposed on various cells were low, in the range 10— 300 milliwatts. Magnetic fields, either from permanent magnets or electromagnets, also seem to enhance heat production.

Heat production with multi-layer thin-film electrodes

Professor George H. Miley, et al, Fusion Studies Laboratory, University of Illinois, have developed a unique process to coat a stainless steel plate electrode (25 mm x 25 mm x 3 mm) with alternating layers of titanium and palladium, which are deposited by a special electron-beam evaporation method. The layers have a total thickness of only 100 Angstrom units, topped off by a 60 Angstrom thick layer of chromium to "act as a barrier to retain a high loading of deuterium or hydrogen." In the reported experiments they work with light water and LiOH electrolyte. They have achieved about 2 kilowatts/cc power production in these thin films. They have actually gone as high as 10 kW/cc, but the layers have a nasty habit of peeling off at these power levels.

Preliminary confirmations of the Kucherov et al glow discharge experiment

Professor Peter Hagelstein of MIT's Department of Electrical Engineering and Computer Sciences showed one gamma ray emission line that this group attempting to replicate the Kucherov et al experiment thinks it has found—a 129 KeV feature that may represent the ^{105}Pd to ^{105}Rh transmutation found by Kucherov et al in Russia. This is only a very preliminary finding.

A group known as "Space Exploration Associates" of Cedarville, Ohio, has obtained preliminary confirmation of gamma radiation in a Kucherov replication attempt. The group was successful in seeing the gammas six times, with no failures. The MIT group is collaborating with them.

A lovely quote from the team's preprint: "It is perhaps worthy to note that Fermi won the Nobel prize for mistakenly believing that he had transmuted uranium by bombarding it with neutrons. So strong was the prevailing belief in the integrity of all atoms that the splitting of uranium was inconceivable. Hence Fermi's experiment was not interpreted correctly at first. Thus, the finding that palladium may be transmuted under the influence of electromagnetic fields in the presence of deuterium may likewise be inconceivable, but may nevertheless be the truth."

(L to R):Dr. Talbot Chubb (Research Systems, Inc.), Dr. Yan Kucherov (ENECO), and Prof. Robert Huggins (Stanford University)

Dr. Martin Fleischmann, in his concluding remarks at the end of the conference, praised Kucherov and said that in France they had reproduced "parts" of the Kucherov experiment.

Dr. Yan Kucherov spoke and reviewed both the thermal excess energy and nuclear effects data that his Moscow group has obtained over the past four years in more than 500 glow discharge experiments in deuterium atmospheres.

Helium-4 results

Evidence continued to build that at least in some varieties of cold fusion experiments, helium-4 (^{4}He) is produced as "nuclear ash." Dr. Melvin H. Miles of the Naval Air Warfare Center at China Lake presented convincing evidence of a correlation between the measured excess power in Pd-heavy water cells and the production of helium-4. His group claims helium production in the range 10^{11} to 10^{12} helium atoms per second per watt of excess power. Dr. Miles said that this is "the correct magnitude for typical deuteron fusion reactions that yield ^{4}He as a product." By this he meant that helium yield would be about right if the powerful 23.8 MeV gamma ray normally associated with the D + D to ^{4}He reaction emerged instead as thermal energy.

The group used metal flasks this time to collect gas samples, instead of the glass vessels used in earlier runs. Critics had complained that the glassware could be a source of contamination by atmospheric ^{4}He diffusion through the glass. Dr. Miles suggested that at the low excess power levels of his recent experiments (~0.1 watt), the possible measurement errors were large, but still he had confidence that the ^{4}He produced exceeded the levels in control experiments (runs with no excess heat).

The group of Professor Daniele Gozzi et al at the University of Rome examined ^{4}He from Pd-heavy water cells by continuous mass-spectrographic analysis—in six cells for over 1,000 hours. They found a correlation in the emergence of helium-4 peaks and rises in excess heat. However, the group is still trying to rule out contamination from atmospheric helium-4 by using the neon-20 (^{20}Ne) measurement simultaneously.

Cold fusion by hydrogen sparking

Dr. Jaques Dufour of Shell Research (France) reported on excess energy produced by sparking onto various metal electrodes in hydrogen gas atmospheres, both light and heavy hydrogen. He reported stable excess energy production of a few watts for periods of several weeks.

Ultrasonic activation—"microfusion"

Roger Stringham and Russ George presented their work. It is clear that they and others who have checked these experiments find substantial levels of ^{4}He after ultrasonic (20 kHz sound frequency) beaming against palladium immersed in heavy water. The ^{4}He is roughly proportional to the excess power evolved, and is said to account for about 20% of that excess. ^{4}He levels are higher than atmospheric concentration, up to 65 ppm, which is on the order of 10 times higher, so atmospheric contamination is unlikely. The excess heat level claimed by this group is at a level of up to 90 watts (input power, 350 watts). The local heating of palladium foils is so great that these occasionally melt through under even continuously circulated heavy water. No observable excess heat or melting was found in ordinary water control experiments. The reaction chamber is normally pressurized to several atmospheres by D_2 and argon gas.

Stringham et al suggest that the collapse of cavitation bubbles created by the ultrasonic transducer at the surface of the palladium injects deuterons into the Pd lattice. The metal lattice, thus locally and rapidly loaded to a high level, gives rise to D + D "microfusion" reactions. On microscopic examination, they have observed evidence for localized ejection of molten metal.

They also claim to have found after testing that isotopes of cadmium are present "skewed in relationship to natural abundance ratios." In particular, they suggest that ^{114}Cd has been formed from the reaction of an alpha particle (^{4}He nucleus) and ^{112}Pd. Measurements made at various laboratories found no tritium, gamma ray, or neutron evolution from the operating apparatus.

Stringham et al, who have a company based in Palo Alto, California, E-Quest Sciences, are offering to sell their "microfusion" apparatus to serious groups as a research tool. E-Quest will guarantee the ability of the device to produce excess power and ^{4}He.

IMRA Japan's work on material properties and triggering parameters

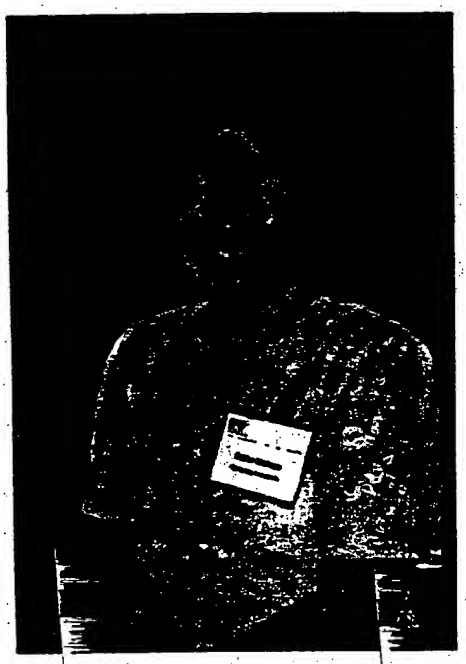
The IMRA Japan laboratory group of Dr. Keiji Kunimatsu continues to pioneer the investigation of alloys, current densities, and loading in Pd-heavy water cells. The group's work in closed cell calorimetry is viewed as among the finest in the world. IMRA Japan uses deuterium gas to pressurize its cells so that the anode becomes a gas-diffusion electrode.

The team has found alloys of Pd using 5% rhodium to be of particular value. IMRA Japan found that Pd materials from different vendors produced excess heat, with one exception. It found excess heat to be "almost proportional" to current density. The critical current required to turn on the excess heat is about 200 mA/Cm^2 of cathode surface area, and the critical loading ratio for turn on was found to be D/Pd=0.84. The addition of thiourea was effective in pushing the loading ratio over 0.9. No excess heat emerged in light water experiments with Pd cathodes.

SRI International's McKubre gears up for nuclear measurements

The EPRI-funded SRI International group, led by Dr. Michael C.H. McKubre, has continued to verify its earlier excess heat work, but is now rapidly mounting a search for nuclear products, including ^{4}He. It wishes "to attempt to quantify the appearance, and set limits on the non-appearance, of po-

tential products of nuclear reactions: neutrons, gamma and x-rays, ^{3}He and ^{4}He, and isotopic-shifts of Pd lattice and electrolyte-derived species." The group made a serendipitous discovery of the beneficial effect on excess power of going to higher temperatures. This temperature effect is now being found almost universally in the cold fusion field.



Dr. Reiko Notoya (Catalysis Research Center, Hokkaido University)

McKubre said that his group has "reproduced, wholly, our previous observations of excess power, and are beginning to study the controlling parameters for the purpose of attempting scale-up."

Tritium production confirmation

Dr. Fritz Will, formerly director of the National Cold Fusion Institute in Utah, and now temporarily with EPRI, reported the reproducible and incontrovertible production of tritium in Pd-heavy water cells that were closed. This work has recently been published in the *Journal of Electroanalytical Chemistry*. It appears to show that tritium can be produced at low energy. Absolutely no tell-tale 14 MeV neutrons were detected that would have been evidence of collisions by T with D in the lattice. Dr. Will meticulously outlined all the reasons to believe that the tritium was generated and could not possibly have been pre-existing contamination. On chance alone, he said in conclusion, it would have required a probability of 1/130,000 to obtain the result of picking the four active electrodes out of the total of 17.

Drs. Tuggle and Claytor of Los Alamos National Laboratory reported continued success in producing tritium continuously and reliably in various "novel morphologies of palladium." They use small solid wires combined with pressed metal powders, and observed tritium production in the range over 5 nano-Curies per hour (>5 nCi/h), which they said "far exceed" their previous results.

The Case of the Missing Scientist

Dr. Kevin Wolf of Texas A&M University was supposed to have been the lead speaker for the December 7 session, but he didn't show up and no explanation was offered. Three high-level sources have seen the data report that Dr. Wolf has discovered astonishing transmutations in three of the palladium rods that he tested in Pons-Fleischmann-type protocols. He has observed many different gamma ray spectral lines from short-lived isotopes. He has no doubt that these transmutations are real. This makes his work similar to the results found by Kucherov in Russia, which was reported in *Physics Letters A*, November 9, 1992.

Unfortunately for Dr. Wolf, he has had an ambivalent position in the cold fusion field after accusations in 1990 by Gary Taubes of fraud in the Bockris lab at Texas A&M. This led Wolf to recant inappropriately his tritium results. Now he can barely imagine associating these extremely intriguing results—in which he allegedly fully believes—with the "discredited" field of cold fusion and transmutation. We know that Wolf wanted to attend the meeting, even though he was going to suggest that these transmutations were really due to cosmic rays from space, which "just happened" to be detected during a cold fusion experiment. It has been learned that he was under great pressure by an opponent of cold fusion,who funds him, *not* to attend the ICCF4 conference.

Hydrosonic Pump continues to evidence excess energy

One of the most unusual presentations at Maui, a last-minute addition to one of the special afternoon sessions, was prompted by a journalist's article. An unusual apparatus came to light as a result of Jerry Bishop's cover story on cold fusion in the August 1993 *Popular Science*. That story prompted Georgia inventor James L. Griggs to contact people in the cold fusion field. He wanted help to explain the baffling excess energy that he and his colleagues had regularly observed with their Hydrosonic Pump.

This device, which has been developed and patented by Mr. Griggs of Hydro Dynamics, Inc. of Cartersville, Georgia as an efficient heating unit for buildings, has regularly demonstrated (it is claimed) significant levels of excess energy. It consists of a specially-designed cylindrical aluminum rotor that spins at close tolerances inside a steel case. Ordinary water is forced through the gap between rotor and case, thus producing hot water and/or steam via turbulent action. The measured energy content of the steam and hot water apparently exceeds the electrical input power of the device by a large margin—10-100% and beyond.

If this effect is real, perhaps this device is related in some way to the cavitation-induced "microfusion" apparatus of Roger Stringham.

Griggs and his colleagues gave a brief presentation at the Maui conference. *"Cold Fusion"* Magazine will continue to investigate the Hydrosonic Pump's performance, and will bring you more news as further testing develops.

Theories abound

At ICCF4, as at previous cold fusion conferences, dozens of papers were devoted to theories that might explain the seemingly bewildering host of experimental findings. *"Cold Fusion"* Magazine will delve into these arcane theoretical matters in a subsequent issue, making a valiant effort to disentangle some of the most difficult issues theorists face. Apologies for this postponement to our theorist colleagues, who perhaps view their efforts as equally important with experimental findings.

We will make one bow toward discussing theory, because ^{4}He nuclear ash has been such a hot topic in the cold fusion field, and because Nobel laureate Julian Schwinger's paper (read in his absence by this author) suggested how a metal lattice reaction generating ^{4}He would not have to be commensurate with excess energy. This is the part of Schwinger's talk ("Cold Fusion: A Brief History of Mine") pertinent to that reaction:

"I note here the interesting possibility that ^{3}He produced in the pd [proton-deuteron] fusion reaction may undergo a secondary reaction with another deuteron of the lattice, yielding ^{5}Li (an excited state of ^{5}Li lies close by). The latter is unstable against disintegration into a proton and ^{4}He. Thus, protons are not consumed in the overall reaction, which generates ^{4}He."

"To this I add, as of some time in 1992, that observations of ^{4}He, with insufficient numbers to account for total heat generated, are consistent with the preceding suggestion. The initial pd reaction produces heat, but no ^{4}He. The secondary reaction generates heat and ^{4}He. There is more total heat than can be accounted for by ^{4}He production. The smaller the ratio of secondary to primary rates, the more the ^{4}He production will be incapable of accounting for the heat generation."

Concluding remarks

Rounding out ICCF4 were summations of the meeting by various senior participants. Dr. Edmund K. Storms, Los Alamos National Laboratory (retired) made one of the most comprehensive and eloquent statements, which *"Cold Fusion"* Magazine has reprinted *(see page 48)*. To summarize, ICCF4 showed that the cold fusion field is becoming ever more vital and expansive—clear evidence of a scientific and technological revolution in the making. Not all papers reported success in finding excess heat and nuclear products, but inexorably scientists are learning the conditions for repeatability of positive experiments, and discovering new methods for generating the phenomena. With small steps and large leaps, the pieces of the puzzle are falling together.

Cold fusion conference

Another leg of the journey

Above all else, the Fourth International Conference on Cold Fusion presented several elemental challenges: that the concept of "cold fusion," after five arduous years, has proved itself experimentally, and that cold fusion is a rapidly maturing science.

It was a conference abundant with scores of papers, seminars, and exchange of ideas for scientists thirsty for developments in the expanding spectrum of cold fusion research.

Organized under the auspices of the Electric Power Research Institute in Palo Alto, California, the conference attracted 274 participants from around the world-more than 150 from the U.S., 72 from Japan, and 34 from Europe, who presented 155 papers. What follows must necessarily be a condensation of thought, theory, and practice derived from the many presentations. Conference Proceedings are being assembled, and soon will be available.

The fifth international conference on cold fusion is set for early in 1995 in Nice, France, and is being organized by IMRA Europe, S.A. in Valbonne, France. Already in the planning stages, the succeeding conference will be in Beijing roughly a year later. One can only wonder at the limitless prospects for end-of-the-century conferences.

A recent industrially-sponsored cold fusion colloquium was held in Asti, Italy, and a conference will be held in Minsk, Belorussia, this May.

Notes and comments on Maui

Two major announcements fell out of the Maui conference, the first a presentation on the New Hydrogen Energy (NHE) Research Project in Japan by Dr. K. Matsui, director of the R&D Center for New Hydrogen Energy in the Institute of Applied Energy in Tokyo.

Initiated in November 1993, the program will run until March 1997 with funding of $30 million from MITI (Ministry of International Trade and Industry). NEDO (New Energy and Industrial Technology Development Organization) is the project coordinator. The program is operated through two major laboratories, the R&D Center for NHE in Tokyo, and the NHE Laboratory in Sapporo. A number of Japanese universities are expected to participate. Cooperation with overseas institutions evidently will be an important aspect of the activity. NHE also will encompass a group of leading industries, including 10 utilities, Tokyo Gas, MHI, Hitachi, Toshiba, Nippon Steel, the Aishin Group, Tanaka Kikinzoku, NTT, IHI, and NFI.

International aspects of the research project apparently will be coordinated through IMRA Europe. The major U.S. partners mentioned were the Electric Power Research Institute, and SRI International.

The program's mission is to clarify the feasibility of New Hydrogen Energy as one of the world's future energy sources. Four major activities were named:

Experimental demonstration of excess heat generation

- Reproducibility
- Verification of reaction products
- Identification of the controlling factors for excess heat generation

Except for a few ill-considered, and rather personal critical remarks by one of the attendees, the conference's tenor was quite normal for an area of newly-emerging science that has possible technological overtones.

Materials science

- Characteristics of existing materials
- Development of new materials

Database and feasibility studies

International Cooperation

- Exchange of personnel and information
- Expert workshops and symposia

The second announcement was that ENECO, Inc. has acquired exclusive worldwide licensing rights to the original Fleischmann and Pons patent applications from the University of Utah. ENECO, founded in 1991, and headquartered in Salt Lake City, is described as a cold fusion research and development company. ENECO evidently has also acquired rights to a number of other patents and patent applications related to the cold fusion area.

The firm brought a number of participants from the former Soviet Union to the meeting. Dr. Yan Kucherov, formerly at the Luch Laboratory in Moscow, is ENECO's director of research. In addition to a modest amount of experimental work in its own laboratory, ENECO is sponsoring small programs at a number of sites in the U.S. and Russia.

General remarks

Except for a few ill-considered, and rather personal critical remarks by one of the attendees, the conference's tenor was quite normal for an area of newly-emerging science that has possible technological overtones.

Earlier results in a number of areas were reinforced by more thorough and quantitative experimental work, and the critical parameters that are responsible for several of the earlier problems have now been established. The spectrum of experimental methods and observations has also been extended considerably. Nevertheless, there are still a number of major unresolved questions relating to the reasons for some of the important experimental observations.

The theoretical basis underlying the now well-established experimental documentation that nuclear processes can take place in solids under conditions that are far removed from those typical of hot plasmas is still far from mature. One of the complicating features is that the reactions expected from hot plasma experience are not found, and that different processes evidently dominate under different experimental conditions.

Identifying "nuclear ashes" has been addressed by a number experiments. The early experimental work in several laboratories that claimed to have *not* observed the Fleischmann-Pons effects has been carefully reconstructed and assessed by independent auditors. The results will be discussed below in these notes.

Excess heat observations in the palladium-deuterium system

The previous experimental observations of excess heat generation during electrolytic experiments were extended and reinforced.

gathers fuel for thought

By Robert A. Huggins

Robert A. Huggins

A number of laboratories reported the results of high quality calorimetry performed using several different methods. This involved experiments with chemically open systems as well as closed, the results being essentially identical when they were performed and analyzed properly.

Fleischmann (Valbonne, France) claimed that his laboratory is now getting excess power output levels of 4 kW/cm³. He declined to discuss the experimental protocols that are being used, but did explain they first load the palladium with deuterium at low temperatures into the endothermic regime, and then quickly drive it to higher temperatures, where it becomes hyperloaded.

Gozzi (Rome) reported on his group's recent multicell experiments, in which they observed both excess heat and the formation of ^4He. In one case, the amounts of heat and ^4He correlated quite well. They concluded, as had others (e.g. Miles) in the past, that ^4He is the dominant "ash."

Kunimatsu (IMRA Japan, Sapporo) reported on his lab's results with closed cells with a partially submerged fuel cell type of positive electrode that recycles the deuterium instead of forming oxygen on the positive electrode. They operated at a D_2 gas pressure of 5-10 atmospheres. This type of electrode reduces the cell voltage below that necessary for water electrolysis, and is the type of setup considered as a possible advantageous configuration in the original Fleischmann-Pons paper.

They showed, as had McKubre (SRI) earlier, that it is critical for the level of loading (the ratio D/Pd) to be over 0.84 in order to observe excess heat. They used a gas pressure measurement method to evaluate the loading. They also found, as both they and others showed earlier, that the amount of excess heat is electrolysis current-dependent, with a threshold value of about 200 mA/cm². They investigated six types of palladium obtained from three sources, and showed that all but one produced excess heat. In that case, they found they were not able to achieve a sufficient loading ratio for some unknown *material* reason.

Their experiments also again demonstrated the well-established fact that no excess heat is observed in light water experiments of this type.

Bertalot (ENEA Frascati, Rome) also presented the Pd/D excess heat results obtained in their laboratory, which they measure with flow, rather than isoperibolic calorimetry. They also use palladium anodes to continually refresh the cathode surface so that it does not become influenced by the deposition of impurities from the electrolyte. They use the pressure change method to evaluate loading. They observed, as have others, that different batches of palladium behave differently, some giving the easily measurable excess heat, and others apparently being "dead." They are now in collaboration with Johnson Matthey, trying to determine the source of this materials effect.

McKubre (SRI International, Menlo Park) reported on their recent excess heat results in closed cells using both isoperibolic and flow calorimetry, and demonstrated that one can obtain comparable results using either method. They have also used open cells in isoperibolic calorimeters of the Pons type, and got similar results. Their open isoperibolic cells have greater sensitivity and a faster response time, and thus provide greater flexibility than the closed flow calorimetric system for the investigation of the influence of various parameters.

McKubre confirmed their earlier conclusion that the D/Pd loading value is critical. When the loading is over 0.95 they always get excess heat, whereas this does not occur with a loading ratio below 0.9.

Using the resistivity method to evaluate loading, they have been investigating the influence of various materials, chemical, and electrochemical variables on the loading kinetics, and the value of the maximum loading obtained. As an example, full loading is never obtained when either nickel or a Pt-Nb alloy is used as the anode. They are also now operating a "movable wire" apparatus to investigate the influence of thermal pretreatment on the behavior of a single batch of palladium.

Another finding is that deliberate introduction of species such as Al or Si into the electrolyte increases the loading and decreases the long-time gradual deloading sometimes found. The use of periodic electrochemical cycling seems to improve the loading.

Most of their experiments are conducted at a constant temperature. However, in one case the temperature rose by mistake, and this resulted in the observation of increased excess heat generation. [See comments below about the influence of temperature reported by others.]

(L to R): Jed Rothwell (Cold Fusion Research Advocates), Charles Becker (ENECO), and Prof. Robert T. Bush (Calif. Polytechnic, Pomona)

Also observed was the difference in the behavior of material from different batches-even from the same supplier. They are working with a palladium supplier to try to understand this effect's origin.

McKubre's group reported it has observed excess heat effects for several days after input power was turned off or way down. This behavior was observed earlier by others (e.g. Mizuno).

Pons showed similar data on significant heat generation for a number of hours after input power was shut off. He called it "heat after death." This only occurred in cells containing D_2O, not in those with H_2O.

McKubre reported another interesting, and perhaps important observation: they have observed a decrease (e.g. 30%) in the base resistivity of the palladium after long time operation. Since the resistivity in metals is due primarily to scattering from point defects, rather than from extended defects such as dislocations or grain boundaries in the lattice, this indicates a change in the point defect concentration with time.

Bockris (Texas A&M, College Station) reported on recent experiments on the influence of various square wave and ramp mode pulsing sequences upon loading, and their influence upon the observation of excess heat when the loading is sufficiently high. He expressed the opinion that dislocations play an important role in the excess heat

phenomenon, and showed the effect of current density (and overvoltage) on microstructural changes in the palladium.

He proposed that the time-dependent exchange of deuterium for hydrogen in the dislocation atmospheres may account for the long incubation (switch-on) time generally observed in this type of Pd/D experiment.

He briefly mentioned the unexpected observation that the imposition of RF (radio frequency) power in the milliwatt range apparently triggers excess heat. Apparently this occurs at a specific frequency. *[See comments below about this.]* There is also some evidence for the influence of magnetic fields, but no substantial information was presented.

Arata (Osaka University) reported excess heat generation using a double (concentric) palladium cathode. Apparently this gives a greater magnitude of excess heat, and for times of the order of months. They observed an incubation time of over 250 hours.

Yoshinaga (Tokyo Inst. of Technology) reported excess heat observations using a square wave loading method in one case out of three. They also observed a much higher overvoltage in the case of the material that gave the excess heat. They had a typical incubation time of 120 hours.

Storms (Los Alamos National Laboratory) discussed his excess heat observations. Storms' group used four batches of material, two showing excess heat, and two not. In the latter cases, he observed a significant volume change due to the generation of cracks and pores. This is in accordance with earlier observations that internal void generation is accompanied by deloading. In one of the two successful cases, he used the SRI technique of adding Al to the electrolyte.

Storms suggested that one could use a measure of the volume change that occurs during loading as a relatively simple and fast way to determine whether a sample of palladium will give excess heat, or will act dead. He said he has only observed excess heat from materials exhibiting less than 2% volume change even if fully loaded. Ones that exceed that amount never give measurable excess heat.

He discussed several critical factors, including the effect of current density (he estimated the critical current threshold to be about 100 mA/cm^2), local surface composition that influences the loading, and the influence of the temperature. It is important that the geometry of the system be arranged so that the current density is relatively uniform around the sample. Otherwise, there is deloading through part of the interface.

Ota (Yokohama National University) showed the results of Pd/D (and Pd/H blank) electrolysis experiments in closed cells. They used both pure Pd and a 10% Ag-Pd alloy, and also found important inter-sample differences, with heat generation in only three of 16 Ag-Pd/D runs. Samples that had prior mechanical deformation produced large heat bursts. They observed gradual deloading of higher current density samples at long times, probably due to the generation of internal voids, as observed by others.

They reported the observation of the current (potential)-dependent diffusion of lithium into the Pd surface with time. [The possible relation between the slow diffusion of lithium into palladium and the observation of much longer incubation times than can be explained by the kinetics of the diffusion of hydrogen species has been a matter of considerable speculation]. Others also reported in-diffusion of lithium.

Miles (Naval Air Warfare Center, China Lake), who was the first to report the generation of ^{4}He in experiments showing excess heat, presented similar results using an all-metal system. His previous experiments had employed glass containers, which led to the criticism that the observed helium may have come from helium diffusion through the glass. He showed that the results obtained with the metal system were comparable with earlier observations, and that the amounts of ^{4}He found correlates quite well with the magnitude of the excess heat he observed.

Oyama (Tokyo Univ. of Agriculture and Technology) performed closed-cell experiments in a double-cell difference calorimeter. Low frequency AC was imposed on top of a DC bias current, and two regimes of behavior were observed, one with relatively stable behavior, the other with unstable behavior. The latter lasted for periods of 50-150 hours. Once excess heat appeared (after increasing the DC current) it remained, even under reduced current.

Cravens (Vernon, Texas) reported on a number of experiments he performed to identify parameters that influence the success of Pd/D electrolytic experiments in producing excess heat. He used both relatively simple open isoperibolic cells, and a flow calorimeter with closed cells.

He observed the microscopic topography and distribution of outgassing sites on the surface of different samples of palladium, and the influence of careful mechanical polishing of the surface on the uniformity of deuterium entry/exit. He found that samples exhibiting substantial surface inhomogeniety do not produce excess heat.

Cravens showed data that indicated the influence of current density and temperature during initial loading upon the final loading level, and thus the excess heat. The best results are obtained by loading at a very low rate until the composition is well into the b ta phase, and then rapidly raising the inp power and temperature.

Preloading with D_2 gas at elevated ten peratures is useful [probably to reduce th hydrogen occupancy of the dislocation a mospheres]. He also had evidence indicatir the advantage of the use of alloys, such : Ag or Rh, that depress the maximum ten perature of the miscibility gap in the Pd. Th presence of lithium seems to help as well.

His data indicated it is helpful to delay th deliberate addition of poisons (promotor such as Al, Si, or B until after the loading well into the beta phase. The geometry (the cathode/anode relationship is also impo tant, as it influences the uniformity of th current density upon the palladium surfac Sharp edges and corners should be avoide He showed that current density uniformity necessary to achieve high loading. Craver also briefly alluded to recent recognition (the influence of small amounts of RF pow and a magnetic field in triggering exce heat events (first reported by Dennis Letts).

It became evident as he spoke that he h shown data relating to several matters othe had been aware of, but had been keeping s cret. Fleischmann said as much, and th may also be true for the SRI activity.

It is now clear that a number of grou know at least some important factors th determine whether excess heat appears du ing this type of experiment. The main poi is that one must be sure that full loading achieved, followed by a sharp jump into th hyperloading regime.

Several quandaries remain, however. Or is the reason for the common observation (a long incubation time. Another is the sour of the large difference in the behavior of di ferent batches of palladium, even from th same supplier. The source of this materia effect is being studied in a number of labor tories. One negative indicator is the form tion of internal cracks and voids, which pr vents full loading, and often occurs.

Heat generation in electrochemical cells containing nickel and light water

Bush (Cal Poly, Pomona) described me surements in a closed system calorimet that indicated excess heat generation at rel tively low input power values. The ratio (excess thermal power to input power w higher the lower the input power, reachin values of 700 or so. They use a fine fibro nickel (or a sintered Ni-Cu) cathode, an various alkali metal carbonates in the ele trolyte.

When using potassium carbonate, Bus claims to have observed the gradual appea ance of calcium in the electrolyte (so di Notoya at ICCF-3). When using rubidiu carbonate, he observes the formation (strontium, which seems to have an isotop

ratio different from the natural one, reducing the probability that this is an impurity effect.

Srinivasan, who reported a number of Ni/H experiments at ICCF-3, is now on a six-month visit at SRI International, where he has repeated experiments previously performed in the BARC laboratory in India. These involved the use of chemically open cells, and he is preparing to do them again in closed cells at SRI.

His results are quite convincing. Experiments in this area are evidently easier to reproduce than the high power Pd/D experiments, and he has done a significant number. His results indicate the magnitude of the excess thermal power generated is essentially independent of the input power. This is consistent with Bush's result that the ratio of output to input powers is highest at the lowest input levels. Taken to the extreme, this would imply an infinite ratio at zero input power.

An interesting aspect of the Srinivasan experiments was his observation that the presence of a stainless steel component in his cells seems to kill this effect—whatever it is. He suspects the presence of chromium is responsible.

Srinivasan reported they have used six types of nickel, and observed these excess heat effects in 14 out of 28 experiments not having stainless steel present. They also found indications of the generation of modest amounts of tritium in some cases. It seems there is no appreciable delay time in these experiments. The maximum value of excess thermal power measured is about 1 Watt.

Criddle (University of Ottawa) also discussed some Ni/H experiments in which he claimed to have observed excess heat evolution. While he gave most of his attention to the influence of silica dissolved from glass containers upon the behavior of the electrodes, it was interesting he found a large difference in the behavior of "soft" nickel and "hard nickel." The latter gave indications of significant excess heat evolution, whereas the former did not. This indicates there is an influence of composition and/or microstructure in the Ni/H experiments as well.

Liaw (University of Hawaii) reported they have repeated their earlier LiCl-KCl-LiD molten salt experiments on the Pd/D system using nickel and lithium hydride, rather than palladium and lithium deuteride. According to this report, they also seem to have found significant amounts of excess heat generation during thermal excursions in this case at about 400°C.

Several people are now convinced that the experimental work of Mills, who first claimed the generation of excess heat in Ni/light water experiments, is sound. Thermacore, Inc. (Lancaster, Pennsylvania) has reportedly reproduced his thermal experiments. Except for Vigier (Univ. of Paris), no one seems to pay much attention to his theoretical model, which attributes the excess heat observations to the formation of a new form of hydrogen, not a nuclear process.

Heat and ^{4}He from ultrasonic cavitation-induced hyperloading

George and Stringham (E-Quest Sciences, Palo Alto) presented another method to provide local hyperloading in the Pd/D system. It involves the use of ultrasonic-induced cavitation in heavy water on a palladium surface. Bubbles are made to adiabatically collapse in a 20 kHz acoustic field such that very high energy microjets of deuterium are injected into the metal surface.

By properly controlling the experimental conditions, acoustic energy arriving at the surface at a power level of 3 W/cm^2 gave rise to a large amount of excess heat-enough to cause melting of several grams of palladium. Calorimetric measurements were reported to indicate the generation of about 90 W of excess heat for periods of several days. This excess heat effect did not occur when the D_2O was replaced by H_2O, or the palladium was replaced by stainless steel.

Large amounts of ^{4}He were found in the heavy water, roughly corresponding to about 20% of the excess heat. Since the ^{4}He levels in the reactor gases were on the order of 65 ppm, which is many times greater than the normal amount in air (5.7 ppm), there was no possibility this observation was due to an air leak. The ^{4}He levels were evidently confirmed by two laboratories.

A third observation claimed that ^{114}Cd was found near the surface of the palladium after the experiment, whereas there was none before.

Efforts are underway to scale up these ultrasonic experiments into the range of several hundred watts. The authors said they would sell copies of their apparatus to a limited number of interested parties, and would warrant that they would produce both excess power and ^{4}He.

Heat From High Pressure Spark Experiments

Dufour et al. (Shell Research and CNAM, Paris) reported on the work at Shell, and what has been repeated and extended at CNAM, Lab. des Sciences Nucleaires in Paris. In these experiments, sparks are passed into metal electrodes through gases containing hydrogen isotopes at atmospheric pressure. The earlier work using this method was described in a paper in the September 1993 issue of *Fusion Technology*. Shell apparently has applied for two patents on the results.

The basic experiment concept is to impose a high local transient electric current (field) in the near-surface region of a metal containing hydrogen isotopes. This transient condition is generated by causing sparks to pass through an atmospheric pressure gas containing hydrogen isotopes. Stable excess thermal power production of about two Watts was reported to have been obtained over long time periods (48-1,000 hours), whereas this was not true for calibration experiments or when using other gases.

In a group of experiments with palladium and deuterium, the total power input in these experiments was about 29 watts, whereas the power input into the spark reactor itself was about eight watts. Thus, the excess power was approximately one quarter of the power put into the reactor, but less than 10 percent of the total power input in this non-optimized experimental setup.

Experiments were also undertaken with stainless steel instead of palladium, and hydrogen instead of deuterium that also apparently indicated the generation of excess heat. This material-independence raises questions, of course.

Measurements of the change of the gas pressure were used to demonstrate that the hydrogen isotopes were actually caused to enter the metal surface by the sparking. These species could be recovered by a degassing treatment at elevated temperature.

Essentially, no tritium or neutrons were observed in these experiments. On the other hand, it was reported that blackening of photographic film was observed with the experiments that showed generation of excess heat, but not with the ones that didn't blacken. This radiation persisted long after the sparking stopped, and was attributed to the generation of electrons with energies about 50 keV.

Sparking was caused to occur at a frequency of 310 Hz, with some five sparks per cycle, and a given spark lasted for about one microsecond. When breakdown occurs, an intense electric current flows on a very local scale, and a current of about 2 A passes through an area of approximately 10^{-7} cm^2. This produces an usually high local field in the metal of about 120 V/cm.

The spark canal is filled with the atomic hydrogen isotope, and this penetrates the surface of the metal, temporarily resulting in a very high localized hydrogen isotope/metal loading ratio.

A reaction model has been proposed that involves three-body collisions in the near-surface region of the metal and is triggered by the high local field. Participants include an electron, a hydrogen isotope, and a third nucleus, and an indirect transition in which a

virtual neutron participates. This model provides a possible explanation for the fact that the observed effects were found with both hydrogen and deuterium, as well as predicting the formation of both ^4He and electrons.

A modification of the experimental reactor was described which makes it act like an ozonizer. In this case, the metal electrodes are separated by either one or two dielectric barriers. The discharge is different in this case, for it involves a large number of very small sparks, rather than one large high current spark. When only one dielectric barrier is used, the spark impinges upon the metal, while this does not happen in the presence of the two dielectric layers.

Researchers observed about 2 watts excess power with the single dielectric layer, so that the spark contacted a palladium electrode. With the second layer, where the spark did not reach the palladium electrode, no excess heat was found. This further reinforced the conclusion that the excess heat effect originates in the metal, not the gas.

This second type of experiment is easier to scale up, and the authors are evidently expecting to move into the range of 100 W excess heat soon.

Plasma (glow discharge) experiments

Kucherov (ENECO, Salt Lake City), who was formerly at the Luch laboratory in Podolsk near Moscow, reported on the many glow discharge experiments that had been performed using palladium targets in dilute deuterium gas.

These well-instrumented experiments have evidently produced a wide range of unexpected phenomena, including excess heat (in 50% of the experiments), neutron fluxes up to 107 n/s, gamma radiation that persisted for days after the power was turned off, charged particles, and both hard and soft x-rays. There are also indications that transmutation reactions occur, as new elements were found to be present after the experiments.

Many details were published in *Physics Letters A* in 1992. ENECO is now funding an effort to try to reproduce these experiments in the Department of Electrical Engineering of the Massachusetts Institute of Technology.

Less comprehensive, but similar experiments were reported by **Kennel** (Space Exploration Assoc., Cedarville, OH). His major conclusion was that gamma radiation suddenly began to appear when deuterium was added to the gas in the system, but that this was not the case upon the addition of hydrogen.

Tritium formation in the Pd/D system

Tuggle, who is in the Claytor group at Los Alamos National Laboratory, reported on the recent extension of their experiments, in which hyperloading is produced in gas-loaded palladium wires and pressed powders by pulsed resistive heating of material previously gas loaded. Their earlier experiments involved passing current through stacks comprised of alternating palladium and silicon sheets.

These new wire experiments have produced a factor of 100 more tritium for the same amount of palladium, reaching rates over five nCi/h (nano Curies per hour). The tritium generation rate is current-dependent, and the results are strongly dependent upon the palladium's impurity content. Samples with over 400 ppm total substitutional impurities produce essentially no tritium. Sulfur has been found to be an especially strong killer. Tuggle has evidence that the tritium is formed inside the solid palladium, rather than on the surface.

Will (EPRI, Palo Alto) presented his very careful study of electrolytic tritium generation in the Pd/D system, recently published (*J. Electroanal. Chem.* 360, 161, 30 November 1993). An important feature of this work was the clear demonstration of the electrochemical parameters' influence on both the rate of loading and the final loading value. As with excess heat observations, full loading (>0.8) was necessary to observe tritium formation. Researchers used a gas volume loading measurement method and an acid electrolyte.

When using a soft cycle loading technique, they obtained full reproducibility (10 times) with material from one supplier, but absolutely no tritium from material from two others. Thus, there is also an unknown "materials effect" in this case as well. Light water experiments conducted in parallel never showed any tritium generation.

Analysis of the palladium samples as well as the electrolyte and gas phases showed that the tritium was formed inside the solid and that it was not uniformly distributed, appearing primarily where the local electrolytic current density, and thus the loading, was the greatest. Observed tritium levels were reproducibly more than 50 times background concentrations. Analysis of a large number (150) of samples clearly showed that the observed tritium did not come from contamination of the initial materials.

As has been repeatedly found by others, the amount of tritium generated in such experiments is much less than that necessary to correspond with the amount of excess heat found in other (higher input power) experiments.

Dr. Jean-Paul Bibérian, a pioneer in solid-state cold fusion.

Mark Hugo (Excelsior, Minn.) (L.) describes at a poster session his basement experiments.

Prof. Steven Jones (Brigham Young University) poses challenging questions.

Generation of excess heat in solid state experiments

There were three reports of the generation of excess heat during elevated temperature electrochemical experiments on proton (deuterium)-conducting solid electrolytes. Two of these, from Russia (**Samgin**, et al. from the Institute of High-Temperature Electrochemistry in Ekaterinburg) and France (**Bibérian** from Marseilles), were presented as posters and were difficult to understand.

The Russian work followed the approach presented in their talk at the Third International Conference on Cold Fusion on the behavior of modified tungsten bronzes, and involved the use of a doped cerate proton-conducting oxide. Researchers claimed the observation of both neutrons and heat generation when conditions were changed. They believe the presence of layers in the solid with different conductivity types is important.

The Bibérian poster dealt with the use of $AlLaO_3$, also known to be a proton-conducting solid electrolyte. Upon application of DC voltages, regions of both n-type and p-type conduction form on the two sides of the solid electrolyte. Although the poster discussed excess heat generation, it was not clear what had actually been measured.

The third was by **Mizuno** (Hokkaido University) who imposed low frequency high voltage (tens of volts) AC across solid state cells with doped $SrCeO_3$-type perovskite electrolytes (0.1 cm thick) and porous platinum paste electrodes. Experiments were conducted in the temperature range 300-500°C in various gases. These materials are known to be proton (and thus deuterium ion) conductors, so that such experiments produce large transient local loading in the solid electrolyte near the electrolyte/electrode interfaces.

They found excess heat generation in the order of 100 W/cm², but only in experiments with these materials in deuterium gas, and not when other (aluminum silicate) ceramics were used that are not proton conductors. They also reported observation of tritium generation, but didn't give further details.

In one example experiment at 410°C, the magnitude of the observed excess thermal power (50 W) was very much greater than the input AC power (18 V and 40 microamperes, or 7 x 10^{-4} W) for a number of hours. This is a very large ratio. The overall heat balance must, of course, include the power input to attain the experimental temperature.

Prof. Bor Yann Liaw (University of Hawaii at Manoa)

Re-evaluation of the early experiments

Three papers, by Swartz (Jet Technology, Weston,MA), Melich (Naval Postgraduate School, Monterey), and Hansen (Utah State University), were presented in which some of the early experiments reporting negative results of excess heat experiments were re-evaluated.

In the hectic period following Fleischmann's and Pons' announcements, efforts were undertaken in a number of laboratories to try to duplicate their results. In several highly visible cases, these experiments' results were negative. In light of current knowledge in this area, several people are interested to know why those laboratories apparently obtained negative results. Harwell experiment data have been carefully evaluated, and it is now claimed that they did, indeed, observe excess heat in two cases, which were hidden by the method of data analysis.

In the second case, precision of the measurements was such that no reasonable conclusions could have been drawn. None of the experiments was conducted long enough to have exceeded the now well-established incubation time. It was also clearly demonstrated that data in another of the highly visible efforts were altered before publication.

Influence of the imposition of RF energy and the presence of a magnetic field

Letts (Energy Research Group, Austin, Texas) offered a poster presentation indicating an apparent effect of both RF energy (at a specific frequency) and a magnetic field in triggering thermal effects in the Pd/D system. These experiments, although described in some detail, for the moment should only be considered as preliminary. They may be indications of something interesting, and other laboratories (including ENECO, Cravens, and Bockris) reportedly are following them up.

Points in connection with the "Materials Effect"

Papers by **Oriani** (University of Minnesota, Minneapolis) and this author's pointed out the great influence of both point defects and extended defects, as well as other microstructural and nanostructural features upon the behavior of interstitial species, such as hydrogen or deuterium, in metals. These matters are well-known in other areas of materials science and engineering, and take them into consideration and interpretation in experiments in this area. It is well established that hydrogen isotopes preferentially reside at dislocations and grain boundaries in metals. They also preferentially enter and exit the solid locally, at the intersections of these structural features with the surface. Interstitial species move rapidly along these defects,

and are also swept along by their translational motion.

Experiments in which metals have been pre-loaded with tritium have been used to demonstrate both the preferential location of hydrogen isotopes at dislocations and grain boundaries, and that they are carried to the solid's surface by dislocations during plastic deformation. Local concentrations can be very different from the average composition. Thus, it is unrealistic to think of interstitial hydrogen isotopes in palladium or nickel as though they are in a structurally homogeneous medium of uniform composition, residing only in normal interstitial lattice positions, and that their transport processes obey Fick's laws for diffusion in a structurally-uniform concentration field.

It would be foolish to continue to consider the whole matter to be related to experimental mistakes, as has been done in some quarters.

Interstitial loading and deloading, especially if this involves formation and propagation of new phases, as is the case for palladium at room temperature, results in the generation of large and inhomogeneous stresses. Phase transitions and dislocation motion are influenced by such local stresses, and are often characterized by delay times and sporadic behavior. It should not be surprising that similar delay times and "burst" characteristics are also found in solid state "cold fusion" experiments.

Two possible dislocation models that could produce transient local hyperloading were described in my presentation. One involves the sudden breakaway of a dislocation from its equilibrium solute atmosphere, leaving the excess interstitial behind. This produces a region of perfect lattice with an extremely high local supersaturation. Another possibility involves the intersection of dislocations and their solute atmospheres moving on different slip planes. When this happens, the superposition of their high local solute concentrations also produces a region in the lattice with a very large local supersaturation.

The role of lithium

Lithium's role in the electrolytic experiments is still not clear. The in-diffusion of lithium has been observed by a number of investigators, and its kinetics seem to correspond roughly to the magnitude of the sample-dependent incubation times that are generally observed in the Pd/D system when the palladium does not already contain lithium. The only experiments of this general type that did not show an appreciable incubation time were those (Stanford and Naval Ocean Systems Center) in which lithium was already present in the palladium.

On the other hand, lithium does not seem to play a role in a number of other types of Pd/D experiments that evidently show excess heat production, such as the cavitation-induced microfusion, atmospheric pressure spark loading, solid state electrolytic hyperloading, and the plasma experiments.

This implies that lithium may well play a secondary role, influencing some other parameter, rather than being involved in the primary phenomenon itself. Because of the large "materials effect," which seems to be related to either the presence or absence of minor compositional constituents—most probably interstitials—or to the microstructure, or perhaps to the interaction of the two, it seems reasonable to suggest that the role of lithium involves its influence upon these.

Hal Fox (Fusion Information Center, Salt Lake City) chairs the Special Topics session.

Closing thoughts

Although there wasn't a great sense of excitement and controversy, ICCF-4 proved to be an interesting conference. A number of things now seem to be well-established, based upon repeated and believable experiments. These include the following:

Excess thermal power *and* energy can be obtained from electrolytic experiments in the Pd/D system. The magnitude, as well a the appearance, of this effect depends upon number of experimental parameters, some c which are not known. If the proper condi tions are met, this can be a large and easil measurable effect.

There is a "materials effect" that prevent the appearance of excess heat in some batche of palladium. The origin of this is not known but it seems to be related to the presence c minor, probably interstitial, impurities.

The observations of small amounts of ex cess thermal power in electrolytic cells wit nickel cathodes and light water carbonat electrolytes also seem to be real, althoug the experimental conditions are very diffe ent from those necessary for the Pd/D elec trolysis system.

Excess thermal power can also be obtaine in a number of other types of experiments i which hyperloading of hydrogen isotopes i caused to occur inside a solid. These includ the high voltage-induced hyperloading in sol id electrolytes, the ultrasonic cavitation load ing experiments, the spark loading experi ments, and the glow discharge experiments. I may well be that one or another of these wi turn out to be more useful in practical appli cations than the Fleischmann-Por electrolyt ic type of experiment.

Products have now been seen in many ex periments that can only be explained b some kind of nuclear reaction. These includ the multiple and well-substantiated observa tions of the generation of tritium inside pal ladium. A number of laboratories have nov observed the formation of ^{4}He, and there ar increasing indications of the appearance o transmutation products. It is possible tha transmutation reactions will explain the ef fects that have been seen in a number of lab oratories involving hydrogen, rather tha deuterium, and that tritium formation shoul be considered in this category. Radiatio and various other products are seen in sever al types of experiments, sometimes in larg and indisputable amounts.

Whatever is happening in the solid stat in these many experiments is definitely dif ferent from the nuclear reactions that occu in hot plasma systems. It also seems that variety of different, but probably related phenomena occur under different conditions

Cold fusion is now a very active area o science worldwide (although with notabl exceptions), and a number of organization are considering ways in which some of th experimental observations might be put t practical use. It would be foolish to continu to consider the whole matter to be related t experimental mistakes, as has been done i some quarters.

Robert A. Huggings is a Professor of Materials Science at Stanford University. H may be contacted at the Center for Solar Energy and Hydrogen Research, Helmholtzstr. 8, 89081 Ulm, Germany.

Patience, patience...

A very "unscientific" and personal take on other cold fusion effects

With special thanks to the skeptics by Edmund K. Storms

I will try to describe the field of cold fusion in five stages. We are now in the transition between Stages 3 and 4.

Stage 1 started when Professors Stanley Pons and Martin Fleischmann partly jumped, and were partly pushed, into the colosseum of public awareness with their claim for low energy nuclear fusion. Sadly, the lions were hungry. Fortunately for Prof. Jones, his claim for a similar but smaller effect was not as tasty to the skeptics.

Pons' and Fleischmann's claim caused every scientist, who was lucky enough to have an imagination and access to suitable equipment, to attempt a duplication of the results. From the smoke and confusion there arose several positive results. These were very carefully examined—and rejected. A few negative results were reported by several well-known laboratories. These were given no examination and were accepted.

Thus began the double standard that has plagued the field ever since. It is germane to point out that recent analysis shows that one of these negative studies could not possibly have produced positive results. One other accepted negative study apparently actually produced small positive results. This stage of unrestrained enthusiasm ended with publication of the ERAB report, a very incomplete and harmful document showing only a minor amount of objectivity.

I would like to suggest an award for those people who most successfully keep the world in the dark. This award would be called the 'Flying Pig Award' in memory of past comments about how cold fusion would be proven real when pigs fly.

The battle was joined

With the advent of Stage 2, the field went underground and became defensive. Work continued at isolated laboratories by people whose special circumstances made them immune to the growing negative attitude. Much of this work wasted time trying to prove the reality of the effect rather than understanding its nature. Frank Close made the case for the skeptics and the message was carried into the lion's den by Douglas Morrison.

Eugene Mallove wrote a clear account of the positive results, and several scientific reviews also supported the reality of the effect. Thus the battle was joined. During this time, the dedicated skeptics actually performed a service to the field. They encouraged better work, and forced an appreciation of the issues. Gradually, the work continued with the support of a few courageous institutions, EPRI being a major contributor to the sparse studies in the U.S.

Stage 3 began when Japan and several other countries initiated major research programs, government and privately sponsored. Significant efforts are under way in India, Italy, Russia, and recently in China. More than 1,000 papers are available in the field—many peer reviewed and many showing positive results. This growing work resulted in improved methods and new ways to initiate the effect.

Presently, more than eight different environments have been found to produce the phenomenon, some completely reproducible. This fact alone should cause some pause on the part of skeptics. In addition, evidence for several different types of nuclear reaction is accumulating. Indeed, some of the results are still too amazing for even people in the field to believe.

Skepticism's new meaning?

As new evidence accumulated, the contribution being made by skeptics changed. In general, they failed to keep up with the field and continued to complain about irrelevant issues. Two recent books by Professor John R. Huizenga and Gary Taubes failed completely to present a balanced view. And to make matters worse, the press has not been much help in presenting the facts. As a result, important issues are not receiving the necessary attention, and unnecessary confusion and even misinformation is being spread. The cold fusion field deserves better treatment. Active skeptics and journalists who distort the facts should consider how they will be viewed should this field eventually be accepted.

On the other hand, by spreading doubt and confusion these skeptics have allowed a few of us to achieve intellectual and financial advantages that would not have been possible had major institutions been in the field.

As a result, many people will be in a very good position to profit when Stage 4 starts. For this reason, some skeptics should be thanked. Therefore, I would like to suggest an award for those people who most successfully keep the world in the dark. This award would be called the "Flying Pig Award" in memory of past comments about how cold fusion would be proven real when pigs fly. Nominees are being accepted.

Stage 3 is now gradually changing to Stage 4, the stage in which the U.S. government and major companies will realize that the phenomenon is real—and vitally important. These new converts will look around for someone who knows how to do competent work in the cold fusion arena—finding few people available. Those of us in the field can, in fact, expect to be awash in money and attention. Only patience is needed at the present time to realize this reward.

Stage 5? This world-changing moment will come when a working device is found on the shelves of a Japanese equivalent of Wal-Mart. This stage is still in the future.

Dr. Storms obtained a Ph.D. in radiochemistry from Washington University (St. Louis) and has recently retired from the Los Alamos National Laboratory after 34 years of service. His work was in basic research in the field of high temperature chemistry applied to materials in nuclear power reactors. His recent studies of the "cold fusion" phenomenon resulted in four publications plus a complete and objective scientific review of the field.

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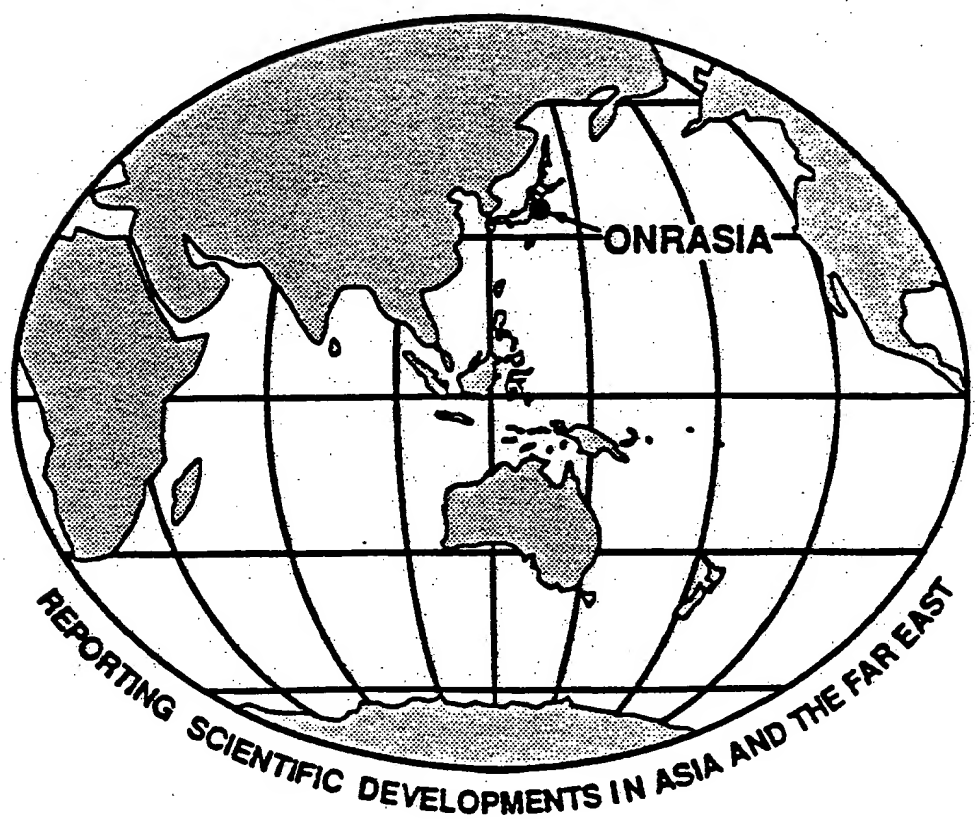

predicted from the resistive heating and the electrochemical energy involved.* They reported power densities greater than 20 W/cm³ of cathode volume. They claimed that such excess heat energy could be generated only from nuclear reactions occurring in the Pd cathode.

Although the claim was immediately supported by Steven E. Jones of Bringham Young University, and a few other more ambiguous reports, most groups, including Pons and Fleishmann, could not reproduce the reported excess heat. Serious challenges were made to the claim of nuclear-fusion reactions by pointing out the high level of nuclear-reaction products (neutrons, tritium, and helium) that would be required if nuclear fusion was the source of the amount of excess heat reported.

The First International Progress Review of Anomalous Nuclear Effects in Deuterium/Solid Systems was held in Provo, Utah, in October, 1990. Confusion and controversy permeated the scientific community, culminating in distrust and suspicion of the integrity of the researchers involved. A review presented by Douglas R. O. Morrison of CERN at the World Hydrogen Energy Conference in Honolulu, HI in 1990 relegated *cold fusion* to pathological science, alongside the infamous N-ray *discovery* eight decades earlier. The term *cold fusion* became taboo, particularly in the United States of America, where most research funding was curtailed, especially by the U.S. Government agencies.

In spite of this attitude, and in spite of the lack of reproducibility and control of *cold fusion*, many scientists agreed that excess heat and low levels of nuclear reaction products were *sometimes* observed. Research continued in Japan, Italy, USSR, China, and India. Even in the United States of America, the Electric Power Research Institute continued to support research at Stanford Research Institute (Michael McKubre) and Texas A&M University (John Bockris). Individual researchers such as Steven E. Jones at Bringham Young, Melvin Miles at the Naval Weapons Center, China Lake, and Edmund Storms at Los Alamos National Laboratory continued research at a low level.

The Second International Conference on Cold Fusion was held in Como, Italy, in June, 1991, followed by an International Symposium on Nonlinear Phenomena in Electromagnetic Field in Nagoya, Japan, in January, 1992. Other reports were published in J. Fusion Energy, Fusion Technology, J. Phys. Soc Japan, Nature, and elsewhere. According to Morrison, 728 papers were published on the subject between the original announcement of Pons and Fleishmann in 1989, and October 10, 1992.

Many papers have confirmed cold-fusion phenomena, but none have been so clear as to constitute generally acceptable scientific proof that nuclear fusion does occur near room temperature in metals. It was made clear, however, what measurements are needed to provide the needed convincing scientific proof.

Two of the more important advances in the understanding of *cold fusion* phenomena prior to the Nagoya conference were achieved by Akito Takahashi and coworkers from Osaka University, Japan, and by Eiichi Yamaguchi and Takashi Nishioka of Nippon Telegraph and Telephone, Ltd, (NTT) Japan.

Takahashi reported refinements of the technique used by Pons and Fleishmann for observing excess heat. In concurrence with McKubre, and with Keiji Kunimatsu, Takahashi emphasized the measurement of the amount of deuterium loaded into the Pd electrode, and the use of a periodic high-low current during electrolysis.

Takahashi reported observing neutron emission at low levels, anomalous tritium production, and formation of He gas at the Pd electrode surface. The observed neutron-energy spectrum supported the occurrence of fusion events, albeit at far too low a level for explanation of the magnitude of excess heat generation observed.

Yamaguchi and Nishioka reported their observation of cold-fusion reactions in a nonelectrolysis environment. They reported high-vacuum studies of deuterium- and hydrogen-loaded Pd plates that had been coated on one side with Au and on the other side with MnO_2 in order to trap and control the deuterium (or hydrogen) within the Pd plates.

Yamaguchi and Nishioka reported concurrent observation of five associated phenomena:

(1) neutron emission bursts (up to 2×10^6 per second);

(2) explosive gas evolution;

(3) uniform warping and plastic deformation of the sample;

(4) the generation of *excess heat* sufficient to heat the Pd plates to more than 700°C; and

* LiOD is referred to by some in this field as "lithium deuterate".

(5) emission of high-energy (≤3 MeV) charged particles.*

The Como conference had little impact on the attitude of the general scientific community toward *cold fusion*. In the first part of 1992, the Takahashi group published a series of papers reporting very careful experiments that showed improved reproducibility of the excess-heat observation at the 150 W/cm³ level. In addition, low levels of ^3H (tritium) emission was reported.

Takahashi and coworkers suggested a theoretical explanation of *cold fusion* in metals to account for the fast-neutron energy spectrum observed. A new concept was suggested: Nuclear fusion reactions involving clusters of two, three or four deuterons or protons colocated near a tetrahedral site of the face-centered cubic (FCC) Pd lattice.

These and other reports from China, Russia, Italy and the United States of America produced a stimulating background for the Third International Conference on Cold Fusion. In Japan, the atmosphere was further charged by news reports indicating that Japan's Ministry of International Trade and Industry (MITI) would consider the results reported at the Conference carefully in formulating plans for possible future investment in research in the field. MITI publicly identified four key factors in their decision:

- detection of neutrons and tritium
- confirmation of excess-energy production
- reproducibility of the results in other laboratories, and
- progress in understanding the physical mechanism.

NUCLEAR ACTIVITY

The paper by Eiichi Yamaguchi and Takashi Nishioka [2] of NTT was highlight of the Third Conference. As mentioned above, in their previous research five concurrent measurements were made to characterize the process giving rise to spontaneous heating of the coated Pd plates. In their current report, a sixth critical concurrent observation was added. Using a high-resolution Extrel mass spectrometry system, they obtained high-resolution mass analysis of the gases evolved from the Pd during excess-heat generation.

These data clearly show the ^4He isotope, as distinguished from other mass-4 isotopes of molecular hydrogen: $^1H^3H$ (proton-triton), and $^2H_2$ (two deuterons, or deuterium). Both of these hydrogen-molecule isotopes have nominal mass of 4 AMU, but differ in actual mass from ^4He by as little as 0.1% because of the lower nuclear binding energy. *In situ* calibration runs of the mass spectrometer demonstrate mass resolution of better than 0.01%.

Yamaguchi and Nishioka report that ^4He and $^1H^3H$ gases are not present in their turbomolecularly pumped chamber unless excess heat generation is occurring in the Pd. The deuterium gas used for *loading* the Pd plate was analyzed *in situ*, and found to contain no detectable ^4He. The conclusion is that these exotic gaseous isotopes (^4He and $^1H^3H$) originate from a *nuclear reaction* with in the Pd:D, and emanate from the Pd during the explosive gas releases that occur only while excess heat is being generated.

In terms of reproducibility, NTT reported that starting in August, five consecutive runs, about a week apart from each other, produced essentially identical results. Other experimenters, at the conference, reported mixed reproducibility. Professor X. C. Li from Tsinghua University, Peking, P. R. China, reported 100% reproducibility, but other researchers reported difficulty in reproducing previously reported excess-heat generation rates. Fleishmann reported that they have never reproduced the high level of excess heat that they observed in 1989. Many researchers reported to have observed excess heat at the range 0.1-10 W/cm³.

Yamaguchi and Nishioka had nothing to report about the possibility of ^3He generation. They plan to retune the EXTREL mass spectrometer for the mass-3 region soon to answer this question experimentally. The generation of ^3He and ^3H is an important question bearing on which of various possible nuclear reactions may be occurring.

The charged-particle results in the NTT experiment are less clear. The charged particle with energy near 3 MeV that was reported previously has been identified as a proton. An alpha-particle peak at 6 MeV is now suspected to be an artifice. The count rates are low in both cases, but especially low for the alpha peak. Also, reproducibility of charged-particle count rates has not been impressive.

It must be clearly noted that, although nuclear activity concurrent with the generation of excess heat seems to have been proved conclusively in the NTT experiments, no one at the conference claimed to

* E. Yamaguchi & T. Nishioka, Jpn J. Appl. Phys. 29 (1990), L666; Proc. Int. Progress Review, "Anomalous Nuclear Effects in Solid/Deuterium Systems" (Provo, UT, Oct 1990), p. 354.

account quantitatively for the excess-heat generation directly from nuclear energy. A major puzzle now is the source of so much excess heat, if not directly from nuclear sources.

In the Yamaguchi-Nishioka experiment and others, neutron count rates up to 2×10^6 per second were observed in bursts. Although their detector efficiency was not discussed, it may be assumed to be a few percent. In later discussions with Yamaguchi, he stated that the reported count rate had been adjusted to account for solid angle, and represents the total for 4π steradians. These neutrons represent at most 10^8 nuclear fusion events per second. However, nuclear-fusion events of order $>10^{11}$/s or more, are required if the watts of excess heat generated are to be attributed entirely to nuclear reactions.

The observation of nuclear reaction products is well correlated with excess-heat generation, explosive gas release, and uniform bi-axial warping, and plastic deformation of the sample. However, the count rates of nuclear-reaction products observed are inadequate to account for the magnitude of excess-heat generation reported.

This may be illustrated by considering typical fusion reactions as follows. The energy release in each case is well known from nuclear-structure studies over the past 60 years:

i) d + d=t(1.0)+ p(3.02)
ii) d + d = ^{4}He(23.85)
iii) d + d = ^{3}He(0.8) + n(2.45)

d denotes deuteron, t denotes triton, and p denotes proton, all nuclei of hydrogen. n denotes neutron. The values in parentheses are the energy release per event in MeV.) Using example ii, which has the largest energy release per nuclear event, 2.6×10^{11} nuclear events are needed per second per Watt, on the assumption that all the energy released is converted into heat, and none is carried out of the sample as kinetic energy of the escaping particle. A neutron count rate of 2×10^6 per second, corrected for detection efficiency and solid-angle of collection, could imply at most 10^{10} nuclear events per second, but the magnitude of the discrepancy is glaring. The discrepancy has proved difficult to account for without assuming a new kind of nuclear process that does not lead to any of the detected nuclear-reaction products.

At this time, the results of the Yamaguchi-Nishioka experiment show that especially strong evidence that some kinds of nuclear reactions do occur in the Pd:D system (and most likely other systems, as well) under appropriate conditions.* In accepting this as a fact of nature, one must also accept the need for a re-examination of the interaction of nuclear states with electronic and other states in solids.

Are new physical concepts active in these systems (such as multibody or other solid-state fusion,) or is some standard approximation of physics being violated (slightly) in certain circumstances? Within physics, the implications are far-reaching. Within technology and society also, there may be far-reaching implications.

Deuterium is abundant on Earth, it comprises 0.015% of all hydrogen, the most abundant element in seawater, and in the astronomical universe. While Pd is a rare and precious metal, Ti and other hosts may work as well. The excess power density recently reported has usually been quite low. Yamaguchi did not discuss the power density obtainable from his Pd plates. However, the NTT experimenters have reported that the temperature of the 3-inch Pd plates rose to as high as 800°C. Temperatures above 500°C can be used to provide high-grade thermal energy useable in efficient commercial production of electricity, for example. Even low-grade thermal energy, if cheap and safe enough, can be useful in architectural space heating, seawater desalination, and other industrial processing.

Because we consider the NTT experiment to be a critical test of nuclear activity concurrent with the generation of excess heat by Pd-deuterium systems, we summarize the significant experimental details.

THE NTT EXPERIMENT

The NTT Pd plates are prepared in a separate vacuum chamber that is normally used for gold evaporation:

First, a thin layer of MnO_x is deposited on a stainless-steel heater.

Second, the 30×30×1 mm Pd plates are mounted in the vacuum chamber and exposed to 1/2 atm of 99.9% pure deuterium gas at room temperature. It is estimated that the deuterium loading factor (the concentration of deuterium atoms absorbed within

* From Pd:H samples, no nuclear reaction products were observed by the NTT researchers. However, explosive gas releases, sample warping, and excess-heat production (smaller) were observed in Pd:H samples, as well.

the Pd normalized per Pd atom) is about 0.48. In the case of hydrogen exposure, the loading factor achieved by this process is estimated to be 0.56. (These values are considerably lower than 0.83, the loading factor generally is considered to be threshold for excess heat production in Pd electrolysis experiments.)

Third, the top surfaces of the Pd plates are rapidly heated by contact to the MnO_x-coated stainless-steel heater, and cooled to room temperature.

Fourth, an MnO_x film 10-20 nm thick is deposited on the surface through electron-beam evaporator, and is followed by 18-24 hr exposure to deuterium gas. The MnO_x film provides a surface barrier for out-diffusion of deuterons, and also a controllable potential well for collection of deuterons with appropriate bias (deuteron-accumulation layer.)

Fifth, after evacuating the chamber to a pressure $p \leq 10^{-5}$ T, a gold film, 200 nm thick, is deposited on the opposite side of the Pd plate from the MnO_x film. This film provides a surface barrier for out-diffusion of deuterons without the possible deuteron-accumulation layer.

Three samples, so prepared, are loaded at once into a UHV chamber. Both standard quadrupolar and high-resolution mass spectrometers are attached to the chamber along with a commercial ^3He neutron detector. The samples are mounted with a strain gage attached (on the Au-coated surface), and a Si charged-particle detector (depletion layer depth: 300 μm). Several thermocouples are used for temperature measurement.

The experiment is controlled by applying current normal to the Pd plate, at the level of 0.5 to 0.8 A/cm^2, or by sample heating. In both cases, it is suggested that migration of deuterium increases the deuterium-loading factor in the accumulation layer beneath the MnO_x insulator. With sample heating, the temperature gradient is said to be the force driving the deuterium migration.

Explosive gas evolution, warping and plastic deformation of the Pd, and excess-heat generation occur with "100% reproducibility," a welcome situation in a field replete with reports of nonreproducibility. The detection of ^4He was added to the experiment only last August, but has been reproducible in five consecutive runs one week apart.

Control experiments using ordinary hydrogen gas loading of the Pd have been conducted as well. In these experiments, excess heat was observed in lesser amounts as well, but no accompanying nuclear-reaction products have been detected.

OTHER EXPERIMENTS

The most quoted experimental research in cold fusion in Japan is that of Akito Takahashi [3] and coworkers. Their well publicized contribution to cold-fusion experimental technique has been copied by several other groups in various countries. The group presented three papers at the Nagoya conference, which updated several of their previous reports.

Previously, Professor Takahashi had suggested that if nuclear fusion can occur in solids in spite of the large internuclear distances, then one may consider whether multibody fusion events might also occur. For the Pd:D and Ti:D systems, Professor Takahashi has suggested events that involve three and four nuclei of hydrogen or deuterium, and that result in emission of reaction products such as ^1H, ^2H, ^3H, ^3He, and ^4He.

In his invited presentation, Dr. Takahashi asserted that cold fusion *is proved*, that three-body fusion products have been identified, and that *a new science of solid-state nuclear physics has been born*, although clearly with scant theoretical basis.

In electrolysis experiments, the Takahashi group uses several periodic modulation methods, achieving excess heat fairly consistently, and in some cases measuring low levels of nuclear reaction products. A low-high alternation of electrolysis current with a 12-hour period, or a saw-tooth ramp, or a six to eight step current-increase pattern are used in open electrolysis cells. The value of the deuterium loading factor is determined to lie between 0.8 and 0.95 in cases where excess heat is generated.

The Takahashi group also reported studies of thin (19 μm) foils of Pd loaded with deuterium from a 250 keV deuteron accelerator. To inhibit out-diffusion, the back side of the foil was coated with Ag (0-3 μm.) Si charged-particle detectors and a micro-channel plate were used to monitor emissions. Although most of the nuclear particles detected were products of deuteron-deuteron scattering, as expected, a small but statistically significant peak in the 3 to 5 MeV energy range lay beyond the 3 MeV cutoff of the deuteron-deuteron scattering products. Further experiments are proceeding, and various experimental parameters are varying.

Titanium is a good host for hydrogen (or deuterium), as well as being an abundant element. Several papers presented considered the possibility of cold fusion in Ti:D systems, in which loading factors up to 1.5 have been obtained. Jiroota, Kasagi [4] and coworkers at Tohoku University reported observations of high-energy protons emitted from Ti upon bombardment with a 150 keV deuterium beam. All protons with energy below about 9 MeV can be accounted for by the normal D(d,p)T reaction and "pileup" peaks related to this.

However, consistent appearance of a broad peak, $12.5 < Ep < 16.5$ MeV, and occasional appearance of a sharp peak at $Ep = 14.1$ MeV were anomalous. The broad peak was interpreted as resulting from sequential reactions: $D(d,^3He)n$ and $D(^3He,p)^4He$. The broadening is due to the isotropic distribution of the kinetic energy of the ^3He created in the first reaction, and its energy loss as it travels through the Ti metal. Calculation of the shape of the broad peak based on the sequential reaction model showed good agreement with the observed peak shape.

The sharp peak at 14.1 MeV is attributed to protons from $^3He(d,p)^4He$, in which the ^3He is at rest after having been stopped in the Ti metal. This is considered important evidence that ^3He is accumulating in the Ti lattice because of the nuclear transmutation during the deuterium loading process. The sharp peak has appeared in only three of 50 experiments, a fact attributed to fluctuations in the structure of TiD_x consistent with the special conditions for nuclear-fusion reactions to occur. Thus the Tohoku group has joined the growing list of investigators who think they have evidence of cold fusion in the Ti:D system.

Presentations of countrywide reviews of cold-fusion research were given by Xing Zhong Li [5], Vladimir Tsarev [6] and Franco Scaramuzzi [7]. They summarized research in P. R. China, Russia and related countries, and Italy, respectively.

Although the number of locations in China that are involved in cold fusion research has been reduced in the past year, a strong and well coordinated research program continues. Li reported a neutron count rate of 8000/s reproducible for more than 18 months. He reported neutron activation experiments on In and Ir foils that give near theoretical lifetimes of 53 min and 19.6 hr, respectively. He reported observation of neutron energy spectra from Nb electrodes that had been loaded with deuterium, helium or hydrogen. The neutron emission count rates for the latter two gases was 100 times smaller than for Nb:D electrodes.

Li expressed the opinion that cold fusion has been confirmed. He concludes that Pd is not necessary, as witnessed by their Nb experiments, but that a film of some metal is necessary. Also, Li referred to the *new science of solid-state nuclear physics*!

A most entertaining and artistic review of research in the now fissioned CIS was given by Tsarev. He summarized 25 papers published in the former USSR during the past year, down from 80 the previous year.

The leading result from this group was Kabir Kaliev' [8] paper, "Reproducible Nuclear Reactions during Interaction of Deuterons with Oxidized Tungsten Bronze." Using Na_2WO_3 single crystals dosed with deuterium, Kaliev claims 100% reproducibility of neutron emission results in 93 experiments. With hydrogen dosing, no experiments gave neutron emission. Some, but not all experiments also produced increasing temperature. Photomicrographs of the Na_2WO_3 crystals showed parallel channels, which were effective diffusion paths for Li atoms. These experiments are currently being checked at Lebedev Institute in Moscow.

Another paper summarized by Tsarev claimed high excess-power generation in a deuterium glow discharge. The best result was 33 W, or 500% excess-power generation. Emission of slow neutrons, fast neutrons, charged particles, and acoustic waves were studied in other Russian experiments. Tsarev summarized that charged particles are 10^6 times more prevalent than neutrons in these experiments, but that 99.9% of the heat generation remains to be accounted for.

Tsarev recalled studies of years ago at Novosibirsk of LiD + D^2O, yielding LiOD + D_2 and weak neutron emission. These studies were confirmed by visiting scientists from Moscow, but never explained.

Scaramuzzi summarized ten papers from Italy. In a subterranean low-background laboratory, no neutron emission was detected from Pd electrodes used in electrolysis, or from deuterium loaded titanium. However, at Padua, 2.5 MeV neutrons were detected from deuterium-dosed Pd and Ti plates. These emissions were in the form of bursts of about 50 hr duration observed after 20 days of cell operation.

THEORIES

A great deal is known about the structure of hydrogen in Pd and other metals. In equilibrium in the Pd:D lattice, a phase of PdD forms in which the deuterium occupies octahedral sites about the Pd atom. The D-D distances are very large: 0.245 nm. Around a Pd vacancy, this distance shrinks to 0.185 nm, still very large compared with 0.074 nm of the deuterium molecule, in which fusion does not occur spontaneously, of course.

Yuh Fukai [9] reviewed the *ABCs of the hydrogen-metal system* for the conference. If two deuterium nuclei were forced to approach each other against the repulsive force of the Coulomb barrier, Fukai asked, at what internuclear distance would the probability of a fusion reaction reach a reasonable level, say 10^{-20} per nucleus per second. Using standard nuclear reaction theory, he obtained the result 0.015 nm, or about a fifth of the equilibrium separation in molecular deuterium. If no screening is assumed, the repulsive Coulomb-barrier energy at that separation is 96 eV, which is much larger than might be provided by phonons or other normal types of lattice interactions.

Of course, screening of the Coulomb interaction must be considered. However, the conduction electron density available for screening the d-d interaction is much too low. The ten 4d electrons of Pd are in a closed-shell configuration, tightly bound to the Pd atom, according to accepted atomic theory. Thus, the density of electrons available for screening the d-d interaction, thereby reducing the strength of the repulsive Coulomb interaction, is completely inadequate. Hence, lattice forces available for squeezing deuterons together are one-hundred-fold too weak by accepted solid-state theory.

Among several attempts to explain cold fusion phenomena using solid-state physics concepts are the papers by Scott Chubb and Talbot Chubb of Research Systems, Inc, Arlington, VA. [10]. They conceptualize an ion band structure for the deuterium ions in the Pd metal, as has been hypothesized previously for hydrogen on metallic surfaces.

By applying the concepts of delocalized, periodic band-structure-type wave functions to the deuterium in the Pd metal, the Chubbs argue for deuterium nuclear reactions that are *not dominated by interactions between individual deuterons*. Invoking the indistinguishability of deuterons as in Einstein-Bose statistics, they argue that the Coulomb barrier that normally prevents two nuclei from approaching each other closely enough for fusion to take place does not prevent fusion of deuterons in the periodic potential of the Pd.

Perhaps the most serious attempt presented at the Nagoya conference for developing a physical theory that allows for significant nuclear-fusion reactions over interatomic distances in metals was presented by Peter Hagelstein of MIT [11]. Using two innovative concepts, Hagelstein calculated the probability of coherent transfer of a virtual neutron to the site of another, remote nucleus. Surprisingly, he found that coherent transfer of a virtual neutron should be possible to nuclei as far as one micron away in the periodic potential of the metal. He reported that Bragg scattering of the virtual neutron should be enhanced by 10^3 to 10^4. He used the Franck-Condon factor to couple nuclear energy with lattice energy via localized vibrational modes surrounding tetrahedral sites (not the normally occupied octahedral sites) in Pd:D.

Giuliano Preparata [12] described his quantum electrodynamical (QED) theory presented in 1989, which will be included in his forthcoming book on quantum electrodynamics in condensed matter. He argues that using QED to describe the screening interaction, the Pd 4d-electrons can be used to effect screening of deuterons as far as 0.7 nm from the Pd atom. In this case, fusion should occur at either tetrahedral or octahedral deuterium sites in Pd.

Jean Pierre Vigier [13] suggested using the quantum electrodynamical vacuum-fluctuation theory of Plutov to describe cold nuclear fusion. He looks for evidence of capillary conduction, which gives rise to Ampere's Law forces that break the capillary into beads. His theory predicts excess heat from electrolysis using H_2O as well as D_2O!

SUMMARY

Three and one-half years after the dramatic initial announcements, cold fusion remains a most highly controversial field of research. Most scientists would agree, probably, that each good research scientist possesses two vital characteristics: curiosity and skepticism. Both characteristics must be present and balanced for the research scientist to function efficiently.

No research exists without curiosity, and no science exists without skepticism. Yet we scientists are mortal human beings with human frailties and

inadequacies. We may neglect, or even purposefully ignore our philosophical principles in certain circumstances.

A scientist, without his natural curiosity, reacts with cynical rejection of any report that conflicts with his current understanding of nature. A scientist, without his natural skepticism, reacts with child-like gullibility to reports of wondrous new observations of nature. Both of these polarizing reactions are noncontributing embarrassments to the scientific community. Both of these extremes were apparent at Nagoya.

Cold fusion, as a field of research, has suffered (and perhaps also benefitted?) from the human lapses of its practitioners and its critics. Both positive and negative effects were abundantly evident at the Nagoya conference. The positive aspect was the stimulating atmosphere for those not so emotion-bound as to be unable to appreciate the humor of the scene, full-grown (yet immature) scientists making fools of themselves before their colleagues and the ubiquitous television cameras!

As a new field of research, cold fusion is more prone to polarizing reactions than other new fields that in recent years have been opened through dramatic discoveries. Experimentally it crosses interdisciplinary lines by involving such disparate fields as electrochemistry, nuclear physics, solid state physics, materials science, and others. Also, the data have been unusually difficult to control experimentally. This circumstance applies great stress on the most fundamental premise of physical science: the infinite reproducibility of experiment.

Theoretically, the explanations suggested by the curious scientists have stretched far beyond the experience of skeptics. This mix of reactions has been psychologically and socially explosive, producing the most deprecative public criticisms recorded by reputable scientists in this century. Clearly this outrageous behavior has not contributed to a dispassionate, scientific evaluation of research results.

A major psychological difficulty was the use of the term *cold fusion*, which invokes images of an inexhaustible source of cheap energy for society, and major deficiencies in current nuclear theory. A more appropriate term suggested at the conference was *anomalous nuclear reactions in condensed matter*. Although it may be too late to prevail upon the scientific community to switch terms, softening the expectations for cheap energy might reduce the emotional extremes and polarization of the scientific community.

Perhaps the clearest scientific fact, at this time, is the hardest for physicists to accept: nuclear reactions apparently do occur in deuterium-loaded Pd, Ti, and probably in other solids. The most exciting claim for technology and society, that of the availability of large quantities of thermal energy in simple electrolytic cells, is the claim that is least reproducible. Even this claim seems to be gaining credibility, although at reduced energy densities. The quantitative connection between the two remains problematic. That fact is a discouraging one for scientists.

For the progress of knowledge, and for assessing the potential technological and social impact of cold fusion, it is important to control reliably the generation of thermal power. Neither science nor technology can progress far without reliable, reproducible experiments. Researchers are working hard toward this goal, and some may have achieved it. It is clear that deuterium loading factors, and all the material parameters involved in that, need to be studied carefully along with schemes to minimize out-diffusion of deuterium.

Nondeuterium systems that have been reported to provide excess heat should be pursued vigorously, seeking the controllability and reproducibility necessary to convert these observations into acceptable scientific fact. Both Mahadova Srinivasan [14], Bom-bay, and Yamaguchi reported excess heat production in systems involving only ^{1}H. In Srinivasan's experiments, the excess heat generation was accompanied by detectable nuclear products, while Yamaguchi found no neutron or charged-particle emission accompanying excess-heat generation in hydrogen-loaded Pd MOS plates. If nuclear reactions occur in ^{1}H-loaded solids, mechanisms beyond those suggested by Hagelstein must be involved.

It seems important to remind ourselves that neither excess-heat generation nor solid-state nuclear events are observed in crystals of natural minerals, for example. If such reactions occur in crystals, which are loaded with ^{1}H or ^{2}H, there must be a trigger or control process that rarely functions in natural materials. On one hand we ask how solid-state nuclear reactions can occur. On the other hand, if we accept as fact that solid-state nuclear reactions do occur, we must ask why they are so rare in our Earth.

It has become clear that a more concerted theoretical effort is now justified to understand, first, whether the occurrence of nuclear-fusion reactions in solids can be justified within current basic

physical theory; and second, how the level of excess-power generation that has been reported might be rationalized with the low level of nuclear reaction products observed.

There is much research to be done before a clear understanding of the phenomena called *cold fusion* can be claimed. Now, it appears to be justifiably on scientific grounds to pursue this goal. Recent news reports in Japan suggest that MITI now concurs in this judgement. When the new budget is submitted to the Japanese Diet in early 1993, MITI's judgement will be apparent. MITI's Hydrogen Energy Study Group, a consortium of industrial researchers, is expected to pursue this subject vigorously. NTT has announced plans to follow up and expand the research results of Yarnaguchi and Nishioka. In all, in Japan, at least, US$10M per year will be spent on research in this field over the next few years.

Certainly China and probably Russia, India, and Italy plan to pursue research in the science of solid-state nuclear physics, and in its potential applications to energy technology, as well. In all, there is reason to believe that a clearer understanding of the science and technology of anomalous solid-state nuclear and spontaneous excess-heating phenomena will be forthcoming.

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THE INFLUENCE OF CONDUCTIVITY ON THE NEUTRON GENERATION PROCESS IN PROTON CONDUCTING SOLID ELECTROLYTES

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The cold fusion process accompanying a generated nuclear emission (neutron, for example) was observed in solids with different conductivity types: in metals[1], tungsten bronzes[2], segnetoelectric[3], and proton conducting solid electrolytes[4, 5]. In this case the investigation of the phase transition influence resulting in a change of conductivity in the neutron generation process is of great importance. The proton conducting solid electrolyte, possessing only protonic conductivity in the high temperature region, was selected as an object of our research. The method of this investigation is described in this volume. The sample's thermocycling after filling the cell with deuterium and electrolysis revealed a neutron emission exceeding the background on the level 4 σ during definite temperature intervals. When a high deuterium pressure was produced in a cell (up to 3 atm), the sample's partial reduction was observed, accompanied by the sample turning black. The sample reduction resulted in a sustained electronic conductivity with air atmosphere at room temperatures. The fact that the neutron generation process stopped after the sample reduction may relate particularly to mixed electronic-cationic to electronic conductivity passage.

The investigation of this deuterium-solid state system's property permits a new interpretation of anomalous nuclear-electron effects. The same behavior is in agreement with one of the main conditions of cold fusion – the formation during deuterium saturation in strongly nonequilibrium conditions of the local inhomogeneous zones with an abnormally increased deuterium atom concentration relative to the lattice atoms[6], with a hypothesis of formatting the regions with dielectrical properties in Pd[7].

Here we may mention that the discovered effect is in agreement with the neutron emission observed in monocrystals of tungsten bronzes[2] during the changing of the alkali metal concentration (for example, by replacing with hydrogen isotopes), which produces semiconductor and dielectrical layers. Current observations also correlate well with the investigations of deuteron emission from solids with segnetoelectric-dielectric or segnetoelectric-ion conduction[3]. This presents peculiarities of the nature of conductivity that may also be useful in understanding both mechanisms which have a common origin in electromagnetic current behavior in dense media, and capillary fusion in special structures with channels[8, 2].

Obviously the nature and the mechanism of conductivity and the existence of multilayered structures with different conductivity types in solids appear to be the additional critical conditions of an abnormally increased rate of nuclear-electron reactions in a solid state deuterium system.

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DEUTERIUM ABSORBABILITY AND ANOMALOUS NUCLEAR EFFECT OF YBCO HICH TEMPERATURE SUPER-CONDUCTOR

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The experimental sutdies of YBCO–D system indicated that YBCO high temperature super-conductor (HTSC) was shown to have a similar effect on deuterium absorbability and anomalous nuclear effect like palladium[1]. We found that $Y_1Ba_2Cu_3O_{7-\delta}$ could absorb deuterium at normal temperature and forms $D_xY_1Ba_2Cu_3O_{7-\delta}$. We also found that the deuterated YBCO could produce high energy charged particles far larger than background. The influence of the absorbed deuterium on the characteristics of YBCO HTSC and the mechanism of the anomalous nuclear effect are not clear and needed to be further studied.

In this experiment the YBCO HTSC sample was prepared by a new technology that high speed direct combine of Y_2O_3, Ba_2 and CuO which were made up on 1, 2 and 3 weight. The zero resistance temperature of the sample was 90°K. The experimental system is sketched in Fig.1. The $Y_1Ba_2Cu_3O_{7-\delta}$ pellet or powder was put on the frame in the vacuum chamber. The CR–39 nuclear track etch detectors which are used to detect charged particles were placed around the sample. The chamber was evacuated to about 10^{-3} torr and then filled with 99.8% purity deuterium of ~ 1 atm. About 1 or 2 days after the CR–39 were taken out and etched and observed in the microscope.

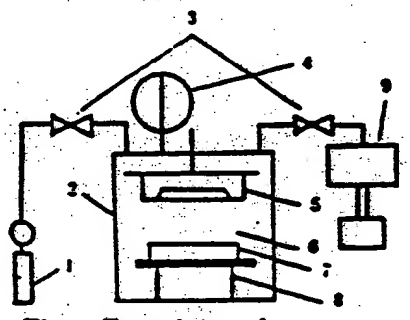

Fig.1. Experimental set up.

1. D_2 tand, 2. Vacuum chamber
3. Valves, 4. Vacuum gage
5. Au–Si surface–barrier
6. YBCO HTSC sample, 7. CR–39
8. Sample frame
9. Vacuum pump

The specific property of deuterium absorption by the YBCO HTSC in the normal temperature is shown in Fig.2. The content ratio of deuterium in $D_xY_1Ba_2Cu_3O_{7-\delta}$ was about x~ 0.2. Fig.3 shows a photo of nuclear tracks on the CR–39. The net number density of the tracks after subtracting the background was ~ $3x10^5/cm^2$. The statistical distribution of the tracks with circular surface mouth on the CR–39 which were produced by the vertically incident particles is shown in Fig.4. For comparison, the statistical distribution of the tracks with circular surface mouth on the CR–39 which were produced

Calorimetric and Nuclear Products Measurements at Glow Discharge in Deuterium

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Abstract

The results of four years of experimental work on glow discharge in deuterium with cathodes made of palladium and other materials are presented. About 500 experiments were made. The typical cathode area was ~1cm², with about 0.1mm thickness. Deuterium pressure was in 1-20 Torr range. Discharge current varied in 10-100mA and voltage in 100-500V range [1,2].

The measuring instruments included slow and fast neutron detectors, neutron spectrometer, NaI and Ge-Li gamma-spectrometers, two-channel charged particle spectrometer with various SSB detectors, X-ray film, activation foil and track detectors, heat loss-type calorimeter. All of the instruments could work simultaneously, except calorimeter-SSB combination.

As a result, maximal measured excessive heat was about 30W and about 10KJ, about ten times the heat that could be produced in chemical reactions with existing deuterium and up to five times the electric input. Excessive heat was observed in about 50% out of 78 experiments in which calorimeter was used. In different experiments heat production was not correlated with neutron or gamma fluxes, but in a separate experiments it was. Maximal Pd-cathode temperature at which nuclear products could be observed was ~ 500°C.

Neutron fluxes with intensity up to 10^7n/s were observed by activation of silver foil, ^{3}He-filled detectors and scintillation detectors. Neutron spectra showed neutron energies up to 17MeV with anomalous shift to high energies (five orders) relative to d-d reaction.

Gamma - spectrometry showed low level radioactive isotopes formation. Together with half - life time measurements it allowed to identify some of the isotopes, such as Rh and Sr isotopes. Most of the lines (~100) are still unidentified. Non-background gamma-lines sometimes can be seen for few days. Most of the gamma-lines appear in lower than 300KeV region. X-ray films outside the chamber with led screens show some beam-like spots with energy 100-200 KeV.

Charged particles registration with SSB and CR-39 detectors showed good correlation of the results obtained by these methods. Maximal observed fluxes of charged particles were ~10^6s^{-1}. SSB detectors which could see the cathode from inside the vacuum chamber and from outside through Be-window showed charged particles with energies up to 18MeV with average energy 2-4 MeV. Degrading foil method showed existence of heavy particles in the spectra (A > 4).

X-ray film with lead screens showed X-ray fluxes up to 10^9s^{-1} with soft (<1KeV) and hard (10-30KeV) components. Sometimes characteristic X-rays of palladium can be seen with Ge-Li detector.

The sum of all measured products carries energy 4-5 orders less than heat release and may be part of registered products are not related to heat effect.

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ELECTROLYTIC HYDROGEN/DEUTERIUM ABSORPTION INTO Pd, Rh AND Pd-Ag ALLOYS IN FUEL CELL TYPE CLOSED CELL

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INTRODUCTION

Significance of high loading by deuterium in palladium cathodes for excess heat generation has been well recognized since the recent works to correlate quantitatively excess heat and deuterium loading ratio D/Pd[1,2]. However, the experimental conditions for the high loading is not fully understood yet because the loading can be influenced by many experimental parameters. The aim of the present report is to review important parameters controlling electrolytic loading of hydrogen and deuterium into Pd and Pd based alloy cathodes based on data obtained in our laboratory. Possible factors controlling cathode loading are: (1) cathode materials, (2) cathode pretreatment, (3) surface modification, (4) electrolyte (5) electrolyte current density or cathode overvoltage, (6) temperature.

EXPERIMENTALS

Experimental details of electrolysis method utilizing a fuel cell anode in a pressurized closed cell for *in-situ* determination of hydrogen/deuterium loading in cathodes have been described elsewhere[2]. The electrolysis was conducted mostly under galvanostatic conditions. The loading ratio H(D)/M, where M stands for the cathode metal, has been determined mostly from the pressure decrease of hydrogen or deuterium gas in the cell after the electrolyte was started. In some cases the loading ratio was determined also from cathode resistance measurements in order to check consistency between the loading data obtained by the two methods.

The effect of cathode materials on the loading was studied by comparing the loading on Pd, Pd-Rh alloys and Pd-Ag alloys. A composite of palladium and silver made by diffusion joint of those plates using a plasma sintering method was also studied and its loading characteristics was compared with other materials.

Cathode pretreatment was standardized to polishing, degassing in vacuo at 200°C for three hours and electrochemical surface cleaning by scanning electrode potential between 0.4V and 1.5 V(vs. RHE) at 50 mV/sec. for ten minutes under hydrogen or deuterium gas before pressurizing the cell.

Effect of surface modification was studied in two ways: firstly by adding catalytic poison such as thiourea which is adsorbed on the cathode surface and inhibits the hydrogen desorption process, $2H\,(adsorbed) \rightarrow H_2$. The organic substance like thiourea can be used only in the fuel cell type cell in which potential of the fuel cell anode during electrolysis is not high enough to evolve oxygen and consequently thiourea is not oxidized at anode. Secondly, the Pd surface was modified geometrically by a sputtered gold film leaving a minor portion of the Pd surface exposed to the electrolyte. The electrolysis current is focused to the exposed Pd surface at which the actual current density could be much higher than the nominal (average) current density over

the cathode surface. The loading of hydrogen into such a Pd cathode would be higher because of the higher cathode overvoltage.

The effect of electrolyte was studied focusing on the difference between acids and bases and in particular on the role of alkali metal cations in the hydrogen loading into Pd cathode. The study has led eventually to loading experiments in alkaline solutions without alkali metals, *i.e.* tetramethyl ammonium hydroxide.

The effect of electrolysis current density was investigated by measuring dependence of H(D)/Pd on current density up to 1 A/cm^2. The dependence was converted to the dependence on cathode overvoltage for hydrogen evolution which was measured with respect to the reversible hydrogen electrode, (Pt/Pt), in the same solution, and was corrected for the IR drop between the cathode and RHE.

The effect of temperature was studied by observing change of cathode loading by hydrogen/deuterium when temperature was changed from 10°C to 60°C. The temperature change was executed in two ways: firstly, cathode loading was determined at each temperature in different cells, and secondly the temperature change was given after the cathode loading of hydrogen in 1M LiOH and of deuterium in 1M LiOD has reached 0.94 and 0.85 respectively at 10°C. The temperature dependence at the high loading conditions both for hydrogen and deuterium were studied in this way.

RESULTS AND DISCUSSION

The results are summarized briefly as follows:

1. All the factors studied have significant influence on cathode loading
2. The cathode loading is strongly reduced by the presence of alkali metal cations, in particular potassium ions, in the electrolyte.
3. High current density is of primary importance for higher loading.
4. D/Pd on Pd higher than 0.9 can be achieved by surface modification.
5. D/M = 1.0 can be achieved for Pd-Rh alloys, where M= Pd + Rh
6. Cathode loading determined by resistance measurement is consistent with data obtained by pressure measurement.

Experimental data to support these conclusions and their significance in the excess heat measurements will be discussed.

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Anomalous Heat Evolution from $SrCeO_3$-Type Proton Conductors during Absorption/Desorption of Deuterium in Alternate Electric Field

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Abstract

The cold fusion phenomena were tested with use of proton conductor solid electrolyte plates maintained at 300~400 ℃. An anomalous level of excess heat evolution of the order of 100 watt cm^{-2} was observed during absorption/desorption cycles of deuterium-containing hydrogen gas under application of an alternate electric field.

1. Introduction

The alleged cold fusion reaction observed is accompanied by a very low and weak level of neutron emission, by occasionally rather a high level of tritium production and by a limited number of cases of low or high level of heat evolution. Nevertheless, reproducibility is generally still poor, as no adequate control of the reaction is possible due to lack of knowledge of its mechanism. It is hopeful that some theoretical attempts have been reported such as the one by Chubb el al.[1] who discussed a high possibility of D-D nuclear fusion in solid state, which may yield ^4He.

A common system widely employed is the electrolysis of heavy water using Pd electrodes, in which one reason of experimental difficulties is that deuterium charging into the sample requires extremely long time. Takahashi[2] observed a large amount of heat generation by employing cyclic changes of current on Pd in heavy water electrolysis. This suggests that a kind of perturbation in electric current may be advantageous. Yamaguchi[3] reported a clear evidence of ^4He production from a Pd plate whose each faces were covered with MnO_2 and Au film, respectively. In this work, the sample was believed to contain comparatively low concentration of deuterium, and it was heated up to several hundred degree centigrade by an electric heater. This may mean that quick raise of temperature is advantageous, in spite of the view that solubility of deuterium is lower at elevated temperatures. However, the condition of heat and other reaction products showed very low reproducibility and no controllability.

Common to these cases, a kind of triggering might be helpful in this reaction. With the consideration that the reaction may occur with a chaotic state caused by the movement of proton in an array of the atoms of the specimen, we have tried to use proton conductor ceramics at suitable temperatures and to apply an alternate electric field.

2. Experimental

2.1 Samples

Samples were made from a mixture of $SrCO_3$, CeO_2, Y_2O_3 and ONb_2O_3 powders. Mixed oxide powder was once sintered in a furnace at 1440 ℃ in air for 24 hrs, and was pulverized, again mixed and filtered to 400 mesh . The powder was pressed to form a plate of 0.8 cm diameter and 0.1 cm thick in a pressing machine and was again sintered in a furnace at 1460 ℃ in air for 24 hrs. Both

sides of the sample plate were then coated with porous Pt film, 0.05~0.15 μm, by applying Pt paste and calcination at 700 ℃ for 24 hrs.

2.2. Measurement

Sample was held with Pt plates of 1 mm thick pressed to both sides and fixed on a copper holder (5 x 4 x 2 cm) with a thin (0.1 mm) mica film in between Pt and a Ni plate which is connected with a stainless steel-coated thermocouple. A heater wire passes through several holes drilled in the copper holder. The holder is fixed with use of stainless steel bolts which were connected to bottom of the metal fitting of a glass jar. The glass jar has a cover flange which has several electric connectors: These connectors were used to introduce thermocouples, electric power lines for temperature control, electric field signals supplied to the sample, etc. Reaction cell is made of a 5 mm thick stainless steel cylinder with 8 cm diameter and 30 cm long.

Sample temperature was kept constant by means of a stabilized power supply. The electric field was supplied from a function generator via. a power amplifier. The electric power was recorded continuously by means of a recorder and two digital voltmeters for current and voltage. Temperature was also recorded by a digital voltmeter at 0.1 ℃ of precision. The pressure of the system was measured by a pressure-to-voltage transducer. Temperature vs. input heater power relationship was calibrated for various gas mixtures.

3. Experimental Results

$SrCe_{0.9}Y_{0.08}Nb_{0.02}O_{2.97}$ and $Al_2Si_{0.8}O_4$ dummy sample, which are placed in the atmosphere of deuterium-containing hydrogen gas. The samples were heated by the heater, and the temperature rose up to a constant level of e.g. 383 ℃ within one hr. The deuterium gas was then introduced into the reaction vessel: Temperature once fell down to 360 ℃, but it again started to rise, attaining 410 ℃ after 5 hrs and this temperature was maintained at least for 20 hrs at which the experiment was terminated. In the other cases of hydrogen gas with the same type of sample or dummy sample in deuterium-containing hydrogen the temperature fell down to about 270 ℃ within one hr and stayed there afterwards. This type of temperature fall should well be accounted for as due to increase of heat loss caused by thermal conduction of hydrogen. A small difference recognized between and hydrogen is probably caused by a small difference in their thermal conductivity.

The heat generation from the proton conductor in the experiment of deuterium-containing hydrogen gas was estimated to be approximately 50 watt (~100 watt cm^{-2}) over 20 hrs, or ~ 3.6 MJ in total. The input power given to the sample was + 18 V, ± 40 μA, or 7.2 x 10^{-4} watt. Accordingly, the output-to-input power ratio was estimated to be as large as 7 x 10^{4}.

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HEAT AND HELIUM MEASUREMENTS IN DEUTERATED PALLADIUM

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Our previous results present a correlation between the measured excess power and helium production in D_2O-LiOD electrolysis cells using palladium cathodes.[2] The measured rate of ^4He production (10^{11}-10^{12} ^4He/s•W) is the correct magnitude for typical deuteron fusion reactions that yield helium as a product.[3] Because helium is present in the atmosphere (5.22 ppm), it is difficult to convince everyone that the ^4He measured in the electrolysis gas is a product of a fusion reaction within the cell. It is indeed a very challenging experimental problem to clearly establish the production of ^4He from Pd/D_2O electrolysis cells. This situation is compounded by difficulties in obtaining large excess power effects in these experiments.

Table I presents the theoretical relationship between the excess power and helium production assuming $^2D + {}^2D \rightarrow {}^4He + 23.8$ MeV as the major fusion reaction with the energy being deposited within the calorimeter. At low levels of excess power, the uncertainties in measurements of the helium and the excess power are rather large. When the excess power exceeds 0.2 W, however, it could be possible to correlate the rate of ^4He production with proposed fusion reactions. It should be noted that for any given excess power, the helium concentration in the electrolysis gas stream will be inversely proportional to the current.

Helium measurements in D_2O and H_2O control experiments are presented in Table II. Metal flasks were used to collect the electrolysis gas samples in order to minimize atmospheric contamination due to helium diffusion through glass.[3] The helium concentrations in Table II support a detection limit of approximately 10^{13} ^4He/500 mL in these experiments as reported previously.[3] Mean values for the measured helium concentrations in these control experiments are 4.4 ±0.6 ppb or 5.1 ±0.7 x 10^{13} ^4He/500 mL.

For experiments producing excess power, five helium measurements using these same metal flasks have been completed. These experiments yield a mean value of 2.0 ±0.5 x 10^{11} ^4He/s•W after correcting for background levels of helium measured in control studies (Table II). This value is once again the correct magnitude for typical deuteron fusion reactions that yield ^4He as a product.[3] However, the excess power levels measured during the collection of the gas samples in these new experiments were less than 0.1 W, hence experimental errors are rather large (Table I). Further experiments using metal flasks are needed that involve equal numbers of control cells and cells producing large excess power effects. This should provide additional statistical evidence regarding helium production in Pd/D_2O electrolysis cells.

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TABLE I. Theoretical Relationship Between Excess Power and Helium Production. Magnitude of Experimental Errors.

P_x (W)	^4He[a] (ppb)	^4He (atoms/500 mL)	^4He Error[b] (%)	Calorimetric[c] Error (%)
0.050	5.6	6.38×10^{13}	18	40
0.100	11.2	1.28×10^{14}	8.9	20
0.200	22.4	2.55×10^{14}	4.5	10
0.500	56.0	6.38×10^{14}	1.8	4
1.000	112.0	1.28×10^{15}	0.9	2

[a] For I = 500 mA assuming $^2D + ^2D \rightarrow ^4He + 23.8$ MeV is the fusion reaction.
[b] ±1 ppb.
[c] ±0.020 W.

TABLE II. Helium Measurements in Control Experiments Using Metal Flasks. No excess power was measured.

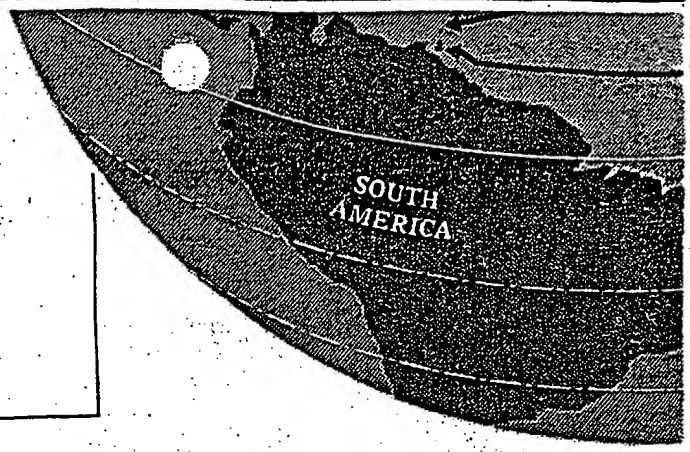
Electrode	Flask/cell	^4He[a] (ppb)	^4He (atoms/500 mL
Pd Rod[b] (4 mm x 1.6 cm)	1/C	4.8 ±1.1	5.5×10^{13}
PdAg Rod[b] (4 mm x 1.6 cm)	2/D	4.6 ±1.1	5.2×10^{13}
Pd Rod[b] (4 mm x 1.6 cm)	3/C	4.9 ±1.1	5.6×10^{13}
PdAg Rod[b] (4 mm x 1.6 cm)	4/D	3.4 ±1.1	3.9×10^{13}
Pd Rod[c] (1 mm x 1.5 cm)	3/C	4.5 ±1.5	5.1×10^{13}
(Mean)		(4.4 ±0.6)	(5.1 ±0.7 x 10^{13}

[a] Helium analysis by U.S. Bureau of Mines, Amarillo, Texas.
[b] D_2O + LiOD (I = 500 mA).
[c] H_2O + LiOH (I = 500 mA).

now = all metal flask

LiOD [0.1 – 0.2 M]

American Origins?
There is ample evidence that pre-Columbian Indians suffered from infection with bacteria called treponemes, which when transmitted sexually cause syphilis. But the evidence suggests that it was not a venereal disease, but a childhood illness, spread by casual contact, like yaws, so that by the time Indians reached sexual maturity, they already possessed immunity.



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Cold Fusion, Derided in U.S., Is Hot In Japan

With plentiful financing and no critics, cold fusion experiments find friendlier ground.

By ANDREW J. POLLACK

Special to The New York Times

NAGOYA, JAPAN

HIDEO IKEGAMI was directing a Japanese research project in nuclear fusion in 1989 when news came from the United States that two scientists at the University of Utah claimed to have produced the phenomenon in a jar. When Japan's Ministry of Education asked him to divert 10 percent of his project's budget to support researchers wanting to explore the new "cold fusion," Dr. Ikegami refused.

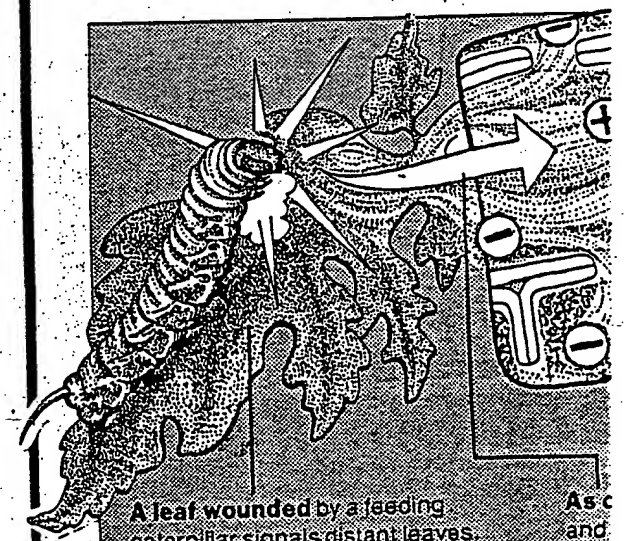
"At that time I thought something like this must be alchemy," he recalled. But Dr. Ikegami, a professor at the National Institute for Fusion Science here, eventually agreed to give up 2 percent of his project's budget to explore the new phenomenon. Now he is doing cold fusion research himself and has become an avid organizer of a Japanese effort that is among the most active in the world.

At a time when many scientists in the United States and Europe have dismissed the idea of room-temperature fusion as an illusion, Japan is pursuing the field with, if not universal enthusiasm, then at least an open mind.

While the United States Department of Energy is not supporting cold fusion research, Japan's Ministry of International Trade and Industry recently decided to spend up to 3 billion yen, or $25 million, over the next four years on what it is calls "new hydrogen energy." About 15 Japanese companies are expected to take part in the effort and to contribute additional money.

Continued on Page C12

Plants Found T



A leaf wounded by a feeding caterpillar signals distant leaves. Recent experiments with tomato plants demonstrate that the signals are electrical and suggest how a plant can signal electrically without nerves.

By CAROL KAESUK YOON

PLANTS, unlike animals, have no nerv scientists have been jolted by the disc this month that the tomato plant us electric signal to alert its defense s against grazing caterpillars.

A team of researchers from England and Zealand reported in the Nov. 5 issue of Nature when a leaf on a tomato seedling is chewed by in it sends out electrical warning signals, alertin rest of the plant to the danger. As undamaged l receive the signal, they begin producing defe chemicals that make them difficult to digest.

"It's a very exciting result," said Dr. Keith erts, head of the cell biology department at the Innes Institute in England and author of the com

ART
The Louvre rehangs a cleaned and repaired Renaissance masterpiece. Page C15

Cold Fusion Is Hot Topic in Japan

Continued From Page C1

A company linked to the Toyota Motor Company is financing the research of B. Stanley Pons and Martin Fleischmann, who first claimed to have discovered cold fusion, at a laboratory in the south of France. And a Japanese precious metals company, Tanaka Kikinzoku, has become the main donor of palladium, the metal needed for cold fusion, to research labs throughout the world.

Japan's interest in the subject was highlighted when seven Japanese scientific societies sponsored the Third International Conference on Cold Fusion here last month, which was attended by 200 Japanese scientists and more than 100 from abroad. Depending on one's point of view, the conference was either a turning point in which evidence was presented that will convince the skeptics that cold fusion exists or a religious revival where claims of miracles were lapped up by ardent believers.

Fusion vs. Cold Fusion

Fusion, the process that creates the heat of the sun and the explosion of a hydrogen bomb, involves the combining of two atomic nuclei, usually of heavy forms of hydrogen known as deuterium. The process usually requires temperatures of millions of degrees, so that taming fusion for energy production is expected to take decades and cost billions of dollars.

But cold fusion researchers think they have created fusion, or perhaps some other unknown reaction that produces a lot of energy, at room temperature by sending an electric current into palladium and platinum electrodes that are immersed in a jar of heavy water, which is rich in the deuterium. If this is true, it could lead to development of a virtually unlimited supply of inexpensive energy.

Supporters of cold fusion in the United States hope that Japan will provide a positive example that will persuade the United States Government the subject is worth funding. If that doesn't work, they will raise the specter of Japan gaining a lead in the technology, a tactic that has worked in the past to elicit Government funding for semiconductors and computers.

"It was invented in the U.S. and there it is, off to Japan," said Dr. Eugene F. Mallove, vice president for research at the Clustron Sciences Corporation, a Vienna, Va., company trying to develop cold fusion generators.

What the Skeptics Say

But skeptics say the Japanese activity should not be a guide for the United States. "Many of the mistakes that I saw in the United States are now being made in Japan," said John R. Huizenga, an emeritus professor of chemistry and physics at the University of Rochester. Dr. Huizenga cochaired a federal review panel in 1989 that concluded that the chances of energy production from the new approach were too remote to justify much Government funding.

To be sure, the level of interest in cold fusion in Japan should not be exaggerated. In Japan, as in the United States, "most scientists don't believe it," said Makoto Okamoto, a professor at the Tokyo Institute of Technology who is working in the field.

The president of the University of Tokyo, Akito Arima, who is a nuclear physicist, said in 1989 that if cold fusion turned out to be real he would quit his job, shave his head and become a Buddhist monk. The other day, through a spokesman, he said he saw no reason to bring out the razor just yet. More than 10 researchers at the university did cold fusion experiments in 1989 but have since quit, having failed to produce excess energy, according to Professor Okamoto.

'A Technological Optimism'

What is different here, some scientists say, is not a difference in scientific beliefs but a greater willingness to gamble.

"There is always a technological optimism in Japan," said Tomohiro Taniguchi, director of the Electric Power Technology Division at the Ministry of International Trade and Industry. He said MITI was now willing to finance research in the field because "We think we already have enough evidence, or at least encouraging evidence, especially after this Nagoya conference."

Particularly influential has been the work of Akito Takahashi, a professor of nuclear engineering at the University of Osaka, who in one experiment claimed to have produced 70 percent more energy as heat than was fed in over a two-month period. His method, which differs slightly from the original work of Drs. Pons and Fleischmann, has since been reproduced in several laboratories around the world, though none has gotten as much excess heat as Dr. Takahashi did.

Another factor is that Japan, which is totally dependent on imports for its oil, is so anxious to develop alternative energy sources that even a long shot is worth pursuing.

"In the energy research area we have been doing many crazy things — and so has the Department of Energy," Mr. Taniguchi said, referring to coal liquefaction, synthetic fuels and other approaches that have not panned out but involved far larger expenditures than what MITI will spend on cold fusion.

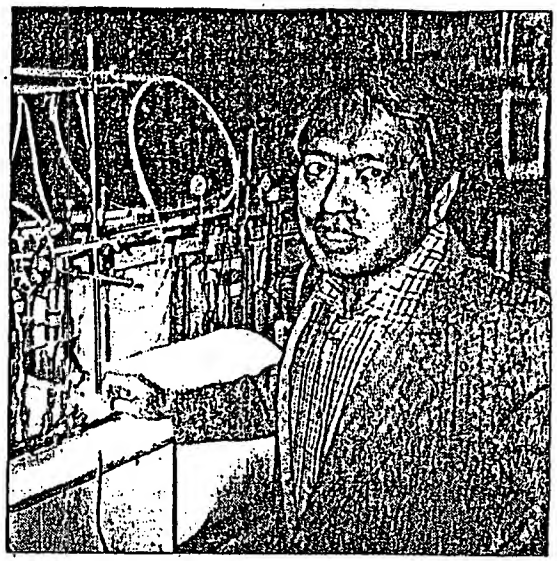
A Cultural Difference

Yet another difference is that even Japanese scientists who are skeptical about cold fusion are reluctant to openly criticize others, in part because of the traditional Japanese desire to avoid confrontation. For that reason, researchers here say they can pursue cold fusion without facing the condemnation that cold fusion researchers in the United States and Europe are said to face.

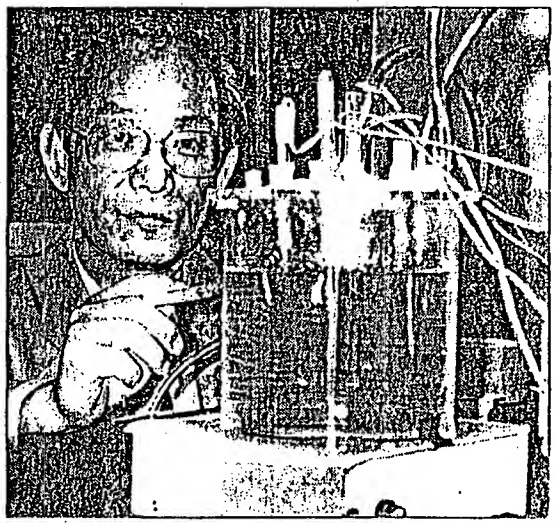
Indeed, Professor Ikegami, who chaired the recent Nagoya conference, said he could not find a Japanese scientist willing to present a paper challenging cold fusion. He ended up inviting someone from Europe instead.

Until now, the 20 or so university groups pursuing cold fusion in Japan have been operating on a shoestring, Dr. Ikegami said. Most of these researchers have been using only the discretionary funds each professor gets, equivalent to about $40,000 per year. In addition, the Ministry of Education program administered by Professor Ikegami, which is now ending, allocated only about $80,000 a year for three years to be spread among many researchers.

The MITI funding therefore will represent a big increase. The nearest equivalent in the United States is the program run by the Electric Power Research Institute in Palo Alto, Calif. The institute, supported by electric utilities, has spent about $4 million on cold fusion so far and its directors have authorized spending another $12 million over the next few years, although the amount is subject to change.



Hideo Ikegami of the National Institute for Fusion Science in Nagoya, Japan, is doing cold fusion experiments and organizing Japanese efforts.



Photographs by Andrew J. Pollack for The New York Times

Akito Takahashi of University of Osaka, with fusion equipment, said one experiment had produced 70 percent more energy than he fed in.

Industry spending in Japan is harder to fathom, but Professor Ikegami estimates it as being $10 million a year.

One of the biggest programs is being conducted at IMRA, a research institute founded by Minoru Toyoda, a member of the family that controls Toyota. IMRA, which stands for Institute of Minoru Research Advancement, is owned mainly by Aisin Seiki Company, a Toyota affiliate that makes auto parts.

Drs. Pons and Fleischmann are working at the IMRA laboratory in Sophia-Antopolos, France. In all, a few million dollars a year is being spent to support about 20 to 25 cold fusion researchers in France and at an IMRA laboratory in Sapporo, Japan, according to Kikujiro Namba, president of Technova, a Tokyo contract research company that is managing the effort.

Dr. Pons and Dr. Fleischmann dropped from view after other scientists questioned their claims and even accused them of fraud, which they denied. But Mr. Namba said Technova, which first invited the two scientists to Japan to discuss their work in 1989, has no qualms about their record. "The only thing we believe is face-to-face dialogue," he said.

When electricity is fed into the cold fusion cell, it splits the heavy water into deuterium and oxygen. The positively charged deuterium ions are absorbed by the negative palladium electrode. What happens next is a mystery.

The evidence that fusion is occurring is that some experiments, such as Dr. Takahashi's, measure more energy coming out as heat than goes in as electricity. Dr. Takahashi said the amount is too great to be attributed to a chemical reaction. In addition, many researchers say they have detected neutrons and other products typical of fusion.

Skeptics, however, say that heat measurements are extremely tricky and prone to error. Critics also say that the amount of neutrons and other products of fusion don't show any correlation with the heat produced.

Dr. Takahashi, who is an expert on neutron detection, said he detected 20 percent more neutrons than would be expected to occur naturally. But he acknowledged that if conventional fusion were occurring, he should have seen 100 trillion times as many neutrons. "That would kill the researcher and the neutron detector itself," he noted.

'A Very Unusual Fusion'

Professor Takahashi thinks that what is occurring is not conventional fusion of two deuterium atoms but "a very unusual fusion" in which three or four hydrogen nuclei combine.

Such multi-body fusion is virtually unheard of but Dr. Takahashi has an elaborate theory to explain how the palladium could act as a scaffolding of sorts to hold the deuterium atoms in position so that three or more,

> A conference is either a scientific turning point or a religious revival.

when they start to vibrate, can fuse together. While he has some evidence to support his hypothesis, it is still just one of many unproven theories.

At the recent Nagoya conference new evidence of fusion was provided by Dr. Eiichi Yamaguchi, a senior scientist at the Nippon Telegraph and Telephone Corporation's Basic Research Laboratories, who said he found helium, a possible fusion product, in his experiment. Instead of dipping electrodes in water, Dr. Yamaguchi saturated a plate of palladium with deuterium in a vacuum chamber.

Other researchers, mainly from the United States, said they could produce excess heat using regular "light" water and nickel electrodes. This is even harder for scientists to accept than the original form of cold fusion. Cold fusion researchers say the evidence is starting to win over people, but some skeptics remain unconvinced. "There was an abundance of claims at Nagoya, some of them far more exotic than I've heard before," said Dr. Huizenga of Rochester. "One group even claimed it can make gold. It's just becoming unbelievable."

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By Jerry E. Bishop
Staff Reporter of The Wall Street Journal

Despite widespread skepticism in the scientific community, a researcher at the Los Alamos National Laboratory in New Mexico asserted that "cold fusion" is a "real" energy-producing phenomenon.

In a soon-to-be-published review of scores of cold fusion experiments, Edmund Storms, a Los Alamos materials scientist who reported tritium in an experiment last year, concludes that an accumulation of results reporting energy production "can no longer be ignored."

The scientist's conclusion coincided with a California physicist's report last Sunday that his "cold fusion" experiment continuously produced more energy than it consumed for 54 days before he shut it down. A unique feature of the experiment was its use of an electrode made of solid silver coated with a thin layer of palladium. Until now most cold fusion experiments, which break up "heavy" water by electrolysis, have used a solid palladium rod as one electrode.

The new reports are unlikely to faze the majority of physicists and chemists who have doubted cold fusion claims from the start. "I haven't seen any convincing experimental evidence that there are any nuclear processes involved," said Richard Petrasso, a "hot fusion" physicist at the Plasma Fusion Center at Massachusetts Institute of Technology. Most physicists say the fact that the experiments produce few if any nuclear particles and radiations is evidence that fusion isn't occurring.

In Mr. Storms's view, however, "It is now far easier and more rational to begin the process of understanding cold fusion as a real phenomenon rather than finding ways to dismiss it."

Of 40 experiments in which heat production was measured, covered in his review written for the Journal of Fusion Technology, the Los Alamos scientist counts 21 experiments in which scientists said they measured more heat coming out than electrical energy going in.

Mr. Storms also counts 13 cold fusion experiments in which scientists have claimed to have detected tritium, an extra heavy form of hydrogen that can be produced in nuclear fusion reactions. In addition, in 36 of 80 experiments, scientists have detected neutrons, subatomic particles that would be produced in fusion reactions, he reports.

The tritium and neutron emissions are far too low to explain the heat output by conventional hydrogen fusion reactions. But, Mr. Storms asserts, the experiments "strongly support" contentions that some kind of nuclear reaction is taking place.

The latest heat-producing experiment was described by Robert T. Bush, a physicist at California State Polytechnic University in Pomona, in a report to the second international cold fusion conference in Lake Como, Italy. Mr. Bush said he and his colleague, Robert D. Eagleton, set up the experiment in mid-April and began recording the production of excess heat nearly four weeks later. The experiment was turned off late last week in order to calibrate the instruments in preparation for his report.

Like many cold fusion experiments, the table-top apparatus consisted of a palladium rod electrode encircled by a platinum wire electrode and immersed in a bottle of water rich in "heavy" hydrogen known as deuterium. The contention is that when an electric current is applied to the electrodes, deuterium atoms worm their way into the palladium and undergo fusion, releasing energy.

Instead of using the usual solid palladium rod, however, Mr. Bush's electrode was a solid silver rod coated with five micrometers of palladium. If this trick works, it would relieve worries of advocates that large-scale use of cold fusion might be limited by the scarcity and expense of palladium.

On a typical day, Mr. Bush said in an interview, his experiment was producing 16 to 17 watts of power while consuming only 12.5 watts, a power gain of about 30%. He asserted that over 54 days, the experiment produced 15 megajoules, or about 14,000 British thermal units more energy than it consumed, a power gain he called "way too high" to be dismissed as a measurement error.

The two chemists who kicked off the cold fusion uproar in early 1989 also were at the Lake Como meeting. But American B. Stanley Pons and his British colleague, Martin Fleischmann, continued to remain silent about details of their latest tests.

In a surprise appearance at Lake Como, however, an independent physicist reported he had found evidence of excess heat production in the raw data from a series of experiments carried out by Messrs. Pons and Fleischmann last year in Salt Lake City. Wilfred Hansen of Utah State University in Logan had examined the unpublished data at the behest of the Utah State Fusion/Energy Council, which had overseen the use of $5 million in state funds for cold fusion research.

"From the data I saw, there was excess heat in a few of the cells," Mr. Hansen said in an interview. He said excess heat production of about 1.5 watts represented a 30% to 40% gain in power. His report, he said, "still needs peer review."

Indeed, "I feel it's difficult to put much stock in these claims until they are written down" and published, so that the actual data can be critiqued, said John R. Huizenga, the University of Rochester chemist who was co-chairman of a 1989 Department of Energy panel of experts that concluded there was no evidence of cold fusion. "One shouldn't be too optimistic at this late stage," he said.

Atlanta Officials Found Liable for Water Pollution

By a Wall Street Journal *Staff Reporter*

ATLANTA—City officials here were found liable in U.S. district court for discharging pollutants into Atlanta's main water supply about 1,900 times in the past three years.

The case, filed by two environmental citizens groups in 1990, now moves to a determination of damages. The courts could fine the city as much as $48 million, or $25,000 a violation, said David Pope, attorney for the citizens groups.

The city's deputy attorney, Mary Carole Cooney, said: "We treat other people's pollutants. Sometimes we can't clean up as much as the law requires." Ms. Cooney questioned, however, how much the city might have to pay, noting that state regulators already have fined Atlanta for many of its violations.

The case centers on sewage dumped in the Chatahoochee River, the city's main source of drinking water, by two city treatment centers. Although state regulators have reprimanded the city and fined it as much as $125,000 for a single five-day violation, the city's own reports, which list 1,925 violations of the Clean Water Act, prompted the suit by the citizens groups.

About 30 such suits have been filed since the mid-1980s, in a new wave of litigation against alleged polluters. Originally, suits targeted companies, but now "municipalities are the major polluters," said Robert F. Kennedy Jr., senior attorney for the Natural Resources Defense Council in White Plains, N.Y.

Quest Medical Acquisition

DALLAS—Quest Medical Inc. said it completed the acquisition of the assets of Clini-Therm Corp. from foreclosure.

On Cellular System Plans Job Cuts

By Jacob M. Schlesinger And John J. Keller
Staff Reporters of The Wall Street Journal

TOKYO—American Telephone & Telegraph Co. and NEC Corp. joined forces to develop the next-generation mobile telephone system in Japan.

The two companies and Fujitsu Ltd. were chosen in November to develop a digital mobile phone network system for Nippon Idou Tsushin Corp., one of Nippon Telegraph & Telephone Corp.'s largest competitors in cellular service. The three companies are also rivals to provide equipment for the network.

Allan Yoshimura, managing director of AT&T Japan's network systems group, said AT&T and NEC have essentially decided to combine their competing bid. NEC and AT&T are trying to make their two systems compatible, so that IDO, as the company is called, can build a system using equipment from both companies.

The two companies are also discussing wider cooperation in the Japanese cellular market, including bidding on other network projects, according to a spokeswoman for AT&T Cellular Systems.

Such a combination would seem to present a formidable challenge to other Japanese cellular network equipment manufacturers and Motorola Inc. of the U.S. Motorola was shut out of the IDO project, but remains one of the top U.S. suppliers in Japan of network radio gear and its flip-top, pocket-sized cellular phone. Motorola didn't return phone calls to discuss the AT&T-NEC linkup.

"AT&T would be an extremely strong factor in the Japanese market and NEC is extremely strong," said Joseph Gunn, senior vice president of Nathan Associates Inc., an Arlington, Va. economic consulting company specializing in the cellular industry. "I'd expect them to make the competitive position of Motorola in Japan very awkward."

The contract for equipment to be used in the IDO network is expected to be awarded soon. Mr. Yoshimura said he didn't know the size of the contract that would be awarded, saying it depended on how successful IDO became.

An NEC spokesman confirmed that the two companies were talking about some form of cooperation in digital cellular phone equipment, but wouldn't give any more details. The news was first reported in Tuesday's Nihon Kogyo Shimbun, a Japanese trade newspaper.

NEC, Japan's largest telecommunications equipment maker, and AT&T earlier this year agreed to cooperate in developing advanced semiconductor manufacturing techniques.

Separately, AT&T said it has named Daniel R. Hesse, a vice president of its International Communication Services unit, president of AT&T Network Systems International, effective Sept. 1. The unit, based in Hilversum, the Netherlands, is AT&T's primary telecommunications equipment subsidiary overseas. Mr. Hesse succeeds John A. Heck, who has been made vice president, manufacturing planning for AT&T Network Systems in the U.S.

Somatogen Receives a Patent

BOULDER, Colo.—Somatogen said it received a patent for blood-substitute products based on hemoglobin, which has been genetically engineered to improve how it delivers oxygen to tissues.

The company, which is trying to develop a blood substitute, said its patent includes claims for hemoglobin variants and how they are used as a blood substitute. The company said the technology was jointly developed by Somatogen and the Medical Research Council in Europe.

By Jim Carlton
Staff Reporter of The Wall Street Journal

Sequent Computer Systems Inc., which expects to report a second-quarter loss that will "significantly exceed" its $7 million loss in the first quarter, said it would move to exit an unprofitable sales operation that once accounted for one-third of its revenue.

The Beaverton, Ore., maker of high-powered computing systems also announced it would dismiss 7% to 9% of its world-wide work force of about 1,700 people, freeze salaries, reduce travel and severely restrict capital purchases.

The company cited the recession and a sharp decline in so-called original equipment manufacturer sales in projecting the loss for the quarter ended June 29, which it said will widen significantly from the first quarter's 30 cents a share. Original equipment manufacturer sales, which the company says it will now de-emphasize, refer to sales to customers that resell Sequent products under their own label.

Drop in Revenue Seen

Revenue is expected to be $49 million to $51 million, up from $47.9 million in the first quarter but down from $58.2 million in the year-ago second quarter, when Sequent reported net income of $5.7 million, or 24 cents a share.

Second-quarter results are expected to be released July 23. The company said the projected loss includes a one-time charge for costs related to the work-force reduction.

Minus the charge, analysts said that equates to an operating loss of $5 million, or 15 cents to 20 cents a share; higher than analysts' estimates that the operating loss would be 10 cents a share for the period.

Following the announcement, Sequent stock fell $2 to close at $9.75 in national over-the-counter trading yesterday.

Scott Gibson, Sequent president, said the quarter was particularly frustrating because the company's sales to end-user customers grew 20% from the first quarter while orders to vendors who resell under their own label fell 50%.

The original equipment manufacturer sales were stagnant for much of 1990 and have been declining since December, primarily because of financial problems experienced by Sequent's largest customer, Unisys Corp., Blue Bell, Pa., the company said.

After agreeing to supply computer systems to Unisys in early 1989, Sequent's resell orders grew that year to $50 million, or 31% of its business, but were projected to decline this year to $34 million, or 13% of its business, with another decrease expected in 1992, analysts said. The company, therefore, said it decided to de-emphasize that business, while shifting focus to the more lucrative end-user sales.

No Canceling of Contracts

"We will not be pursuing much new business [in orders for resale]," said Sequent spokesman Grant Kimball, adding the company isn't canceling contracts with Unisys and its other big customer, Siemens Nixdorf Inc. in Germany.

The move drew praise from analysts. "If it's a drain on the expenses and you can't reverse a negative trend, it seems like you might as well cut your losses," said John B. Jones, managing director of Montgomery Securities in San Francisco.

Analyst J. Neil Weintraut with Hambrecht & Quist said that, long-term, Sequent's exiting the resale business would help restore profitability. "But the company still has to get its financial results back on a strong footing, which will likely take into the fourth quarter," he said, citing the continued weak economy, among other factors.

results would be essentially identical to those Needleman published in 1979—namely, that for every 10 parts per million increase of lead in a child's tooth there was a two point drop in IQ. Paul Mushak, a consultant in health and chemical sciences in Durham, North Carolina, sharply disputed Ernhart's contention that Needleman had not fully cooperated with a 1983 investigation of his work conducted by a panel of the EPA. Finally, Joel Greenhouse, a statistician from Carnegie-Mellon University, criticized the statistical methods used by Marsh's panel to conclude that something might be amiss with Needleman's research.

Since his work was first challenged, Needleman has insisted that any questionable analyses or data reporting that appeared in the 1979 paper would fall under the heading of scientific difference of opinion, not misconduct. And he says he asked for an open hearing to make that point clear. "I shudder to think what would have happened if it had been closed," he told *Science*.

He is also trying to fend off the charges more directly: He has asked the courts to toss out the whole investigation. Last month, he filed a class-action suit in federal district court against NIH, OSI, and Pitt claiming that the definition of misconduct as "practices that seriously deviate from those that are commonly accepted within the scientific community for proposing, conducting, or reporting research" is too vague, and virtually impossible to defend against. The suit also argues that it is unfair to investigate him for events that occurred before the current misconduct rules came into effect. And Needleman claims that since he was not allowed to be formally represented by Lieber during last week's hearing (although Lieber sat at his elbow throughout the day) or subpoena witnesses—he wanted NIH fraud-buster Walter Stewart to testify—his constitutional right to a fair trial was violated.

The Cooley panel hopes to wrap up its work by the end of this month, and Needleman will have a chance to comment on their findings. But Needleman's lawyer worries that even an open forum will not protect scientists from attacks from those seeking to discredit their work, as he claims Scarr and Ernhart have done. "They've taken a research debate and turned it into a blood sport," he says.

Still, there may be more open forums like this if Needleman's strategy appears to work to his advantage. "As a rule, it is the accused who has the most to lose [in a misconduct case]," says Paul Friedman, dean for academic affairs at the University of California at San Diego medical school, so if he or she asked for an open hearing, "it would be very difficult to deny the request." If he's right, misconduct hearings could become even more of a spectator sport in the 1990s.

–Joseph Palca

COLD FUSION

A Japanese Claim Generates New Heat

They're back—claims of cold fusion, that is. Actually, they never really went away. The original experiments by chemists Stanley Pons and Martin Fleischmann may have been discredited in the eyes of many observers soon after they were hailed in 1989, but die-hards around the world have continued churning out reports of excess heat when an electric current is run through chunks of palladium immersed in heavy water. Last week, Akito Takahashi added his claims to the pile. And even in a field where eyebrows have become permanently raised, Takahashi has managed to cause a bit of a stir.

Takahashi, a professor of nuclear engineering at Osaka University in Japan and a respected specialist in the physics of conventional hot fusion reactors, has issued one of the most startling claims since Pons and Fleischmann themselves. He says his cold-fusion cell produced excess heat at an average rate of 100 watts for months at a time. That's up to 40 times more power than he was putting into the cell, and more power per unit volume (of palladium) than is generated by a fuel rod in a nuclear reactor.

Takahashi, who had previously announced his results in Japan, made his first U.S. presentation at—of all places—the Massachusetts Institute of Technology (MIT), home of some of cold fusion's loudest and most derisive critics. "I was worried," said Takahashi afterward. "I thought everyone would attack me." As it happened, many of the attendees praised Takahashi's experimental innovations...but then again, most of the skeptics had stayed home.

Among the innovations that caught the fancy of attendees: Instead of the usual palladium rods, Takahashi used small sheets, which he guessed might make it easier for deuterium atoms from the heavy water to snuggle into the crystal lattice of the metal and—he hoped—undergo fusion. He also kept varying the current in the cell, guessing from the bursts of heat seen in earlier experiments that the process might thrive under transient conditions. His reward, he told the MIT audience, was so much heat that he had to lower the average current repeatedly and install a cooling coil to keep the water in the cell from boiling. Even then the temperature continued to rise week after week. Finally, he said, "we were very much afraid of an accident, and had to stop." As well he might have been, considering the January explosion of a cold-fusion experiment at SRI International in Menlo Park, California, (*Science*, 10 January, p. 153) that killed a researcher.

Missing neutrons. Among the largely sympathetic audience, a few doubters asked pointed questions about the calibration of the calorimetry—the measurement of heat output—and other possible sources of false readings. Nor has Takahashi shaken the biggest doubt plaguing claims of cold fusion: the lack of the plentiful neutrons any nuclear process should produce, according to current physics. Indeed, Takahashi's neutron readings were not only low; they were inversely correlated with heat production.

For many physicists, that closes the door on any claims of fusion. "If it's a nuclear process, known or unknown, it has to be producing on the order of billions of times as many particles as are being observed here," says Richard Petrasso, one of a small group of physicists at the MIT Plasma Fusion Laboratory who have made a virtual pastime out of shooting down cold-fusion claims. "Where are the particles? It's a lot easier to believe the calorimetry is at fault than all of nuclear physics."

Cold fusion supporters would rather look beyond standard theory. MIT electrical engineer Louis Smullin echoed the views of several supporters at the Takahashi presentation when he told *Science*: "You might be able to argue that with better calibration you'd only get 50 watts instead of 100 watts, but 50 watts is still a big number. I'm not concerned about the lack of the neutrons you would expect from a [conventional] fusion reaction. This is a different ballgame, and it could be a different reaction."

Indeed, cold-fusion aficionados are already positing exotic processes that could account for the Japanese observations. Takahashi himself speaks of a four-body nuclear reaction that yields no neutrons at all. And Peter Hagelstein, an MIT x-ray laser researcher who has been focusing on cold fusion for the past 3 years, asserts in a paper to be published in the *Journal of Fusion Technology* that neutrons are emitted in cold-fusion reactions—but are promptly absorbed by the palladium lattice.

But those proposals aren't making cold fusion claims any more palatable to the physics community as a whole. For now, Takahashi and hundreds of other researchers keep laboring over their (gently, they hope) bubbling cells, recording their provocative output and trying to ignore the chorus of voices saying they are wasting their time.

–David H. Freedman

David H. Freedman is a free-lance science writer in Brookline, Massachusetts.

C+E News March 30/92

Cold fusion takes a licking, but keeps on ticking

March 27 was the third anniversary of the announcement of cold fusion. To mark the occasion, advocates for cold fusion research held a press briefing in Washington, D.C., where they bitterly attacked the scientific establishment for its rejection and disregard of the controversial phenomenon.

The event was marked by a new level of public vituperation and frustration on the part of the advocates over what they see as the scientific community's closed mind to the notion that nuclear fusion can occur readily inside a metal lattice.

The briefing featured two of the staunchest advocates—Eugene F. Mallove and Giuliano Preparata. Mallove is an engineer and author of a recent book favoring cold fusion. Preparata is a professor of theoretical physics at the University of Milan, Italy, who has proposed a theory to explain it.

C&EN staff photo

Mallove: gross scientific misconduct

They did not announce any new insights into this phenomenon, which the vast majority of physicists and chemists finds unconvincing. But they reviewed what they regard as the most "promising" results discussed during the past year at cold fusion conferences in Italy, Japan, and elsewhere. Japan, Mallove says, has become a hotbed of cold fusion research, although the latest, most exciting results reported there haven't yet been published.

Most cold fusion experiments involve interaction of deuterium atoms with a palladium electrode, as in a heavy-water electrolysis cell. According to Mallove, the evidence implicating a nuclear process includes "massive amounts" of excess heat that cannot be explained by any known chemical processes, as well as "weak traces" of tritium, neutrons, and charged particles. It appears to be a wondrously clean reaction, he says.

And that is precisely why most scientists find it unbelievable: The amount of excess heat claimed is vastly out of proportion (by a factor of 10^8) to the meager amounts of fusion by-products measured. Ascribing this heat to a nuclear reaction, when no commensurate amounts of nuclear products are observed, is described as "illogical" and "unscientific" in a new book, "Cold Fusion: The Scientific Fiasco of the Century," by John R. Huizenga. A professor of chemistry and physics at the University of Rochester, N.Y., Huizenga has extensively investigated cold fusion claims. And he says they violate the "well-founded results and principles of nuclear physics."

Preparata and a few other physicists, on the other hand, believe that new physics has been uncovered, although the details are not understood. The scientific establishment is hostile, Preparata charges, because it "cannot tolerate an abrupt change in the paradigm."

Mallove and Preparata spent most of the two-hour press conference lashing out at persons (such as Huizenga) who they believe have stymied general acceptance of cold fusion. Among those attacked were researchers at several prominent institutions who have said they looked for—but found no evidence of—cold fusion. Their published reports were instrumental in turning scientific opinion against cold fusion. Mallove, however, insists those negative results are "very weak" or "have problems."

In particular, Mallove accuses researchers at Massachusetts Institute of Technology of "gross scientific misconduct and fraud" for misrepresenting, as negative results, raw excess-heat data that appear to be faintly positive. The MIT researchers have said those seemingly positive data are not significan At the time those results were pul lished, Mallove was chief science wri er at MIT's news office. He resigne that post last June in protest.

Also assailed at the press conferenc were John Maddox, editor of *Nature*, an associate editor David Lindley. Bot have scoffed at cold fusion and, accor ing to Mallove, refused to publish lette from electrochemists who claim to ha found algebraic errors in published, ne ative results. *Nature*'s position is th these letters did not have scientific mer

Mallove believes that the "arroganc and "vested interests" of some scientis and journal editors are keeping the tru about cold fusion from getting out. Hu zenga, in his book, says advocates li Mallove "are unwilling to accept t negative experimental evidence on cc fusion, and look for all kinds of oth unrelated reasons to explain why t subject is slowly dying."

Nevertheless, Mallove expects to s some commercial cold fusion produ in this decade. Indeed, notes Prepara chemist B. Stanley Pons recently to Italian journalists he expected a dem stration device to be unveiled before end of the year. Pons, who with cowo er Martin Fleischmann introduced world to cold fusion, is reporte studying the phenomenon at a corpor laboratory in Nice, France, with fund from a Japanese consortium.

In the U.S., no significant federal state money is allocated for cold fus research, says advocate Jed Rothw However, the Electric Power Resea Institute, the R&D arm of the U.S. e tric utility industry, has been func some exploratory research.

Mallove and Rothwell want Cong to appropriate at least $10 million ar ally for cold fusion research, and h petitioned the House Committee on ence, Space & Technology to hold h ings. So far, more than 350 researc and enthusiasts have signed the peti But the committee has not been re tive. Frank Murray, staff director o Subcommittee on Energy, calls a hea "probably the worst possible setting" evaluating the scientific merits.

The newest tack Mallove is takir to try to replicate what some pr nents hail as exciting, though un lished, excess-heat results from Ja He is pursuing these experiments i home basement in Bow, N.H.

Ron Dc

Making the case for 'cold fusion'

At MIT, Japanese scientist describes test; some say he made a good case

By David L. Chandler
GLOBE STAFF

A scientist from Japan, where "cold fusion" has remained a hot topic long after it was dismissed and largely abandoned by Americans, came to the Massachusetts Institute of Technology this week to try to convince that bastion of skepticism that his experiments show that the phenomenon is real.

The scientist, Akito Takahashi of Osaka University, said his device consistently put out 70 percent more power than it consumed, over a two-month period, by a process that could not be explained on the basis of known chemical reactions. He concluded that the heat was caused by a new form of fusion – the nuclear reaction that powers the sun and stars.

Some MIT physicists at the meeting said Takahashi had made a better case than earlier presentations, but none appeared to have changed their positions as a result. Skeptics continued to raise questions about the experiment's methods, while several believers, in earnest conversations outside the lecture hall afterward, said their views had received strong support.

"There has to be something extraordinary going on in the cell," Takahashi declared. The device generates 1,000 times more heat than chemical reactions could achieve, based on known chemical laws and the known components present in the device, he said, so it may be a form of "unknown nuclear fusion."

But Richard Petrasso, a physicist at MIT's Plasma Fusion Center who attended Takahashi's talk, said he had seen "no evidence of nuclear processes." Although he has long been a critic of the cold fusion claims, which he thinks have been based on scientific errors, Petrasso said that Takahashi gave "a very credible talk," and that unlike some other researchers in the field, "he showed you some details."

The experiment Takahashi described was very similar to the original one performed by B. Stanley Pons of the University of Utah and Martin Fleischmann of the University of Southampton in England, whose announcement caused a worldwide furor in March 1989, when they said they had found a way to produce fusion power using a relatively simple tabletop apparatus. The report set off a spate of reports that envisioned a nearly inexhaustible and clean source of electricity.

The excitement gave way to accusations of sloppy science or even deception, however, as many laboratories around the world found they could not reproduce the results Pons and Fleishmann had reported. But over the years, a few researchers in various government, industry or university laboratories have continued to find tantalizing and enigmatic results that have kept the controversy alive.

Takahashi's results have been loudly trumpeted by Japanese newspapers and magazines, and research on the so-called cold fusion process has received substantial funding in Japan. US funding for such research has been virtually eliminated since reports that challenged the validity of the early experiments.

The experiments are based on immersing two pieces of palladium, a rare metal similar to platinum, in a jar of "heavy water," or deuterium oxide, and connecting the metal pieces to opposite poles of a battery. After a time, some researchers say, the device begins producing more energy, in the form of heat, than the device is receiving from the battery, and that the excess is too great to be explained by chemical processes. They conclude that fusion – the joining together of atoms with a great release of energy – is taking place. Fusion ordinarily happens only at temperatures of millions of degrees.

While Fleischmann and Pons used pencil-size metal rods, Takahashi used thin square sheets of palladium, about the size of postage stamps, and instead of a steady electrical power supply he varied it regularly. He said his heat-output results appeared to have been more stable and predictable than those of the original experiment.

A physicist at MIT, Philip Morrison, said yesterday that he is "quite convinced that there is a source of excess heat" in the experiments, but not that it is fusion. Because the calculations involved are very complex, he said, it would be easy for a small error to give rise to what appeared to be large heat outputs.

He said experiments so far have not done an adequate job of measuring in detail the energy that goes into the system. "Until that's done," he said, "I'm not going to be too interested in the thing as some kind of miracle."

Petrasso said he thought there was a "one in a trillion" chance that the claims of cold fusion are correct. "I think these guys are honest, I just think they're mistaken."

AP PHOTO

A Japanese researcher, Akito Takahashi of Osaka University, offers details of his cold-fusion research findings Wednesday night at MIT.

PHYSICS

POWER IN A JAR: THE DEBATE HEATS UP

A radical new theory claims to get energy from distilled water

RESEARCHERS BUSH AND EAGLETON: "EARTH-SHAKING" IMPLICATIONS?

[TOP TO BOTTOM] PHOTOGRAPH BY MICHAEL GRECCO/SYGMA; ILLUSTRATION BY LISA KNOUSE BRAUMAN

Nearly four years have passed since two noted chemists, Martin Fleischmann and B. Stanley Pons, mesmerized the world with the claim that cheap energy could be gotten from water using a simple electrochemical cell. After months of work by hundreds of labs failed to replicate "fusion in a jar," most scientists rejected the idea. Some even branded it "con fusion."

Cold fusion won't go away, however—and its proponents are preparing a fresh assault on traditional science. Some 300 of them will gather in Nagoya, Japan, on Oct. 21 for the Third International Conference on Cold Fusion. The hot news there will be the first confirmation of radical claims from Robert T. Bush, a physics professor at California State Polytechnic University in Pomona. Building on an idea from Randell L. Mills, president of HydroCatalysis Power Corp. in Lancaster, Pa., Bush says he has triggered a reaction by dunking a nickel rod in distilled water salted with common chemicals. The discovery is "earth-shaking," he says. If it holds up, adds Fleischmann, "it's one of the events of the millenium."

Bush and Mills use the same electrochemical approach as Pons and Fleischmann but their ingredients differ. Pons and Fleischmann passed an electric current between a platinum wire and a palladium rod immersed in water made with deuterium, a heavy form of hydrogen. They suggested that once the current had packed the rod with deuterium, its atoms began to fuse, giving off more energy, in the form of heat, than was in the electric current. Mills and Bush replace the palladium cathode with nickel and the heavy water with regular "light" water or a mixture of both forms. And they propose that the heat is generated by totally different reactions.

Most scientists had a tough enough time swallowing the claims of Fleischmann and Pons. To physicists in particular, the notions of Mills and Bush are even more outrageous. The problem has always been that the claimed cold-fusion results violate established theories of physics, which hold that fusion is far more likely in the presence of tremendous heat. Attempts by Bush and others to concoct a new theoretical framework have further alienated physicists, who tend to explain the claims of surplus energy as experimental error.

Ironically, even Mills and Bush dispute each other's work. Mills sides with the physicists who insist that whatever is happening can't be fusion because the expected nuclear-reaction by-products aren't produced in sufficient amounts. "It's a chemical reaction," Mills insists. He believes that under special conditions the electrons circling hydrogen atoms give off energy when they "collapse" into previously unknown orbits. To physicists, that's heresy.

So is Bush's theory. He believes the excess energy comes from "electrochemical alchemy." When protons, or hydrogen atoms stripped of their electrons, are driven onto the surface of the nickel cathode, something happens—Bush doesn't know what—that causes the protons to fuse with an electrolyte in the water. "That's nonsense," declares John R. Huizenga, professor of physics and chemistry at the University of Rochester. Getting the nuclei of small atoms, such as hydrogen or deuterium, to fuse is tough enough, he adds. For atoms as large as sodium, the chances are almost nil.

BHABHA WATER. To the doubters, Nagoya will be a page from *Believe It or Not.* Mahadeva Srinivasan, head of the Neutron Physics Div. at India's Bhabha Atomic Research Centre (BARC) near Bombay, will report that more than half of 30 light-water experiments since January have produced 20% to 70% excess energy. Japanese scientist Reiko Notoya from Hokkaido University's Catalysis Research Center will report measuring 200% to 300% surplus energy from an experiment she began in August.

More support for the light-water approach comes from Thermacore Inc., a

COLD FUSION II

Despite skepticism, researchers have given up on cold fusion. Various scientists are claiming tests produce more energy than they consume:

Experiment location	Net energy yield claimed
CALIFORNIA POLYTECHNIC, POMONA	50%–200%
HYDROCATALYSIS, LANCASTER, PA.	900%
BHABHA RESEARCH, BOMBAY, INDIA	20%–70%
HOKKAIDO UNIVERSITY, JAPAN	200%–300%

*Produced as heat.
Sustained over more than 12 months.

DATA: BW

defense contractor in Lancaster that specializes in heat-exchange technology. Since April, it has been running a Mills cell that steadily pumps out four times the energy that's put in, says Robert M. Shaubach, manager of development. Mills himself claims to do better. "We're getting 10 times the power out relative to power going in—every hour, every day, week after week." Mills says to expect a "major announcement" around yearend that his confidants predict may include the unveiling of a prototype 10-kilowatt electrical generator. To Peter L. Hagelstein, an electrical engineering professor at Massachusetts Institute of Technology, such talk is premature. After reviewing Mills's data, Hagelstein says: "I don't think the light-water results are there just yet."

Mills isn't the only one eyeing commercial possibilities. Bush, who claims to get up to 700% surplus energy from cells built by fellow Cal Poly physicist Robert D. Eagleton, has signed on with Fusion Energy Applied Technology Inc. (FEAT), a Salt Lake City startup founded by Harold L. Fox, who publishes *Fusion Facts* newsletter. FEAT has just secured modest funding from a private investor to build a Bush-style prototype generator. "We hope to have it ready in nine months or so," Fox says.

> One critic says that claims of huge amounts of excess heat are so preposterous 'you can dismiss them out of hand'

Meanwhile, even stranger research is starting up, aimed at developing solid-state fusion cells that dispense with electrochemistry. For example, physicist Frederick J. Mayer, founder of Mayer Applied Research Inc. in Ann Arbor, Mich., is working on fusion "marbles." Initially, Mayer says, he was dubious of cold fusion. But if his work pans out, he envisions little balls of deuterium-packed metal inside ceramic coatings. In theory, heating the balls would trigger a self-sustaining reaction that would continue until the deuterium is exhausted.

Mayer's idea may not be as fanciful as it sounds. Scientists at Nippon Telegraph & Telephone Corp.'s Basic Research Labs in Tokyo have been experimenting with solid-state systems for three years. NTT puts magnesium-oxide-plated palladium squares in a pressure chamber filled with deuterium gas or, more recently, hydrogen—the gas-based equivalent of a light-water experiment. After the squares, roughly 1 inch on a side and 0.05 inch thick, have soaked up gas atoms for 40 hours, they're plated with gold to seal in the deuterium or hydrogen. If a square is later heated or jolted with a current, it starts generating heat. NTT says the output continues for at least 50 minutes, producing from 0.5 watt to 1 watt of energy.

BAD SCIENCE. The lack of independent verification leaves skeptics adamant, however. Claims of huge amounts of excess heat are "preposterous," says Huizenga. "You can dismiss them out of hand." He and other mainstream physicists blame bad science or experimental error. That could be if excess heat levels were 10% or even 30%, Mills says. But when the excess is 100%-plus, "there's no way it can be erroneous," he argues.

A formal review may soon shed light on this question. The Electric Power Research Institute (EPRI) in Palo Alto, Calif., has budgeted $12 million of its utility members' money for cold fusion research and hired SRI International to do it. MIT's Hagelstein is impressed with SRI's heavy-water experiments, which produce net energy almost every time and show signs of precise control. When input power is scaled back, heat output dips proportionately, instead of doing nothing or responding counterintuitively. Now, EPRI has asked Brookhaven National Laboratory to examine SRI's work, and Brookhaven senior physicist Kelvin G. Lynn, a cold-fusion doubter, has agreed to do it. "My colleagues were very critical" of this decision, he says, "but part of me has admiration for the people that work on this." The review is on hold pending agreement on Lynn's insistence that crucial details won't be kept secret on proprietary grounds. Otherwise, "I couldn't be a fair evaluator."

Bush asserts that Nagoya "could be the turning point" in helping cold-fusion advocates gain respect. Chances are, though, that nothing could do the trick like a thumbs-up from Lynn.

By Otis Port in New York, with John Carey in Washington, Neil Gross in Tokyo, and Gary McWilliams in Boston

COLD FUSION'S DISCOVERERS GO FAR FROM THE MADDING CROWD

JOHN BAIR/GAMMA-LIAISON

FLEISHMANN AND PONS: QUIETLY WORKING IN FRANCE

The chemistry professors who precipitated the cold-fusion ruckus—B. Stanley Pons and Martin Fleischmann—take heart in the results being reported by researchers following in their footsteps. But Pons and Fleischmann know that vindication, if it ever comes, is probably years off. "We couldn't believe it ourselves for the first five years" before going public in 1989, says Fleischmann.

Hounded by charges of slipshod science and even fraud, the pair dove underground in mid-1989. Eventually they resigned their academic posts at the University of Utah and Fleischmann at Britain's Southampton University and set up a lab in Sophia Antipolis, France. Fleischmann won't discuss how much funding they have. But the money, channeled through Technova Inc., a Tokyo think tank, is from a multinational consortium.

IN SPURTS. Pons and Fleischmann are sticking by their heavy-water approach, though some cold-fusion advocates believe it may be superseded by newer light-water techniques. Randell L. Mills, president of HydroCatalysis Power Corp. (page 88), claims his light-water setup has generated heat continuously for more than a year. Fleischmann and Pons' best cells produce excess heat in short spurts.

Whatever the process, Fleischmann is confident that it's only a matter of time until cold fusion's secrets are unlocked—because "the people who have had all these positive results aren't going to give up."

nvesting in Research

AL Staff Reporter

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325S to $1,195 to
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mpaq's 325S equiva-
slightly higher-qual-
$1,312, while IBM's
priced at $1,629.

NTT Says Evidence of Nuclear Reaction Was Found in 'Cold Fusion' Experiment

By Jacob M. Schlesinger And Jerry E. Bishop
Staff Reporters of The Wall Street Journal

TOKYO — Nippon Telegraph & Telephone Corp. jumped into the "cold fusion" controversy with a claim that one of its scientists had found "direct evidence" of a nuclear reaction in a cold fusion experiment.

The telecommunications giant said that the scientist had detected the presence of helium-4 in each of five similar but separate experiments. The helium wasn't present when the experiments began but appeared within the first two to three hours, the company said. Helium-4, the most common of the two forms of the inert gas, can be created by the fusion of two atoms of deuterium, a "heavy" form of hydrogen.

The original cold fusion claim made in Utah in 1989 assumed that the heat energy allegedly coming from a bench-top water electrolysis experiment was produced by the fusion of nuclei of deuterium atoms. One reason the claim met widespread disbelief among physicists was the lack of the expected by-products of nuclear fusion such as radiation and/or helium or tritium, a super-heavy form of hydrogen.

Two other laboratories, both in the U.S., have previously reported finding helium-4 in cold fusion experiments but doubtful physicists raised the possibility of inadvertent contamination of the experiments. Whether the new NTT claim will be more acceptable won't be known until Saturday when the scientist describes his experiments at an international cold fusion conference in Nagoya and later publishes details of the experiment.

Nevertheless, the NTT claim, which was made in a news release, illustrates the heightened interest by the Japanese in cold fusion research. Another company that is putting some research money into the experiments is Imra Japan Inc., set up by the Aisin Seiki Co. group which, in turn, is controlled by Toyota Motor Corp., the auto maker. In addition, experiments by the two chemists, B. Stanley Pons and Martin Fleischmann, who made the original cold fusion claim in 1989, are understood to be funded by Japanese interests.

The Japanese Ministry of International Trade and Industry (MITI) has earmarked 300 million yen ($2.5 million) this fiscal year for what it cautiously calls "new hydrogen energy" research and expects to pour an additional one billion yen into the effort in the next three years. And Japanese scientists at universities in Sapporo and Nagoya have recently claimed successful cold fusion types of experiments.

In the U.S., the only major support for cold fusion research is the $3 million a year the industry-supported Electric Power Research Institute is putting into a single laboratory at SRI International, the contract research institute in Palo Alto, Calif. A cold fusion researcher at California State Polytechnic University has been receiving $80,000 a year from Southern California Edison Co. and a handful of small experiments are being supported by individual Americans.

The U.S. Department of Energy ended all funding of cold fusion experiments in late 1989 when a panel of experts said it remained unconvinced that such a phenomenon had been found. General Electric Co., which put some scientists into the original cold fusion laboratory in Utah in 1989, is no longer actively involved in the field but is "monitoring world developments," said a spokesman at the company's research laboratory in Schenectady, N.Y.

NTT said Eiichi Yamaguichi, a 37-year-old scientist at the firm's Basic Research Laboratories, "succeeded in observing direct evidence of cold nuclear fusion." "This success will be an important step toward the realization of clean energy for the future," the company said.

At a news conference, Dr. Yamaguichi said that he had taken a small plate of palladium metal, coated with gold on one side and manganese oxide on the other, and saturated it with deuterium. The palladium was put into a vacuum chamber and heated. After two to three hours the chamber contained helium-4 atoms that hadn't been present before, he said.

The experiment differs from most cold fusion experiments in which electrodes of palladium and platinum are immersed in deuterium-rich heavy water and subjected to an electric current. During the electrolysis of the heavy water, it's claimed, fusion of deuterium atoms inside the palladium releases several times as much energy as is consumed.

Pfizer Inc.

Pfizer Inc. launched a new heart drug that it predicts will be one of its largest-selling products by the mid-1990s.

The drug, Norvasc, is a calcium channel blocker approved as a treatment for hypertension and angina. Analysts have predicted sales of the drug will reach $500 million within two to three years. A company spokesman declined to comment on analysts' projections.

Pfizer already has a calcium channel blocker, Procardia XL, on the market and analysts have wondered whether Norvasc would cannibalize sales. Pfizer has maintained that the drugs will "complement rather than compete with each other."

Procardia XL, its largest-selling drug, represents only 7% of the cardiovascular drug market. Moreover, Procardia XL is used primarily by patients with moderate to severe heart disease, while Norvasc will be targeted at the mild to moderate end of the spectrum, a company official said.

First City Bancorp. Of Texas Says Bank Sale Tops Forecast

By a Wall Street Journal Staff Reporter

HOUSTON — First City Bancorp. Texas, which is trying to sell several of smaller banks as part of a recapitalizati plan, said it received bids in excess of $210 million it initially expected.

The bank holding company also said reached agreements in principle to rene date leases on properties it occupies several Texas cities, a development could allow it to add about $80 million to capital of its banks in Houston, Dall Austin and San Antonio.

The transactions, which remain subj to final agreements and shareholder a regulatory approval, are key parts of Fi City's effort to rescue itself without res ing to federal assistance. Although fede regulators initially were understood to skeptical about the plan, which also wo require that the Federal Deposit Insura Corp. forgive $60 million owed it by F City, a First City spokesman said reg tors now "seem to be impressed what we're doing." The FDIC couldn't reached for comment.

Another major hurdle in the recapi lization plan is the raising of $100 millio a combined private placement and ri offering. The company's chief finan officer, Robert W. Brown, said First Ci seeing "lots of interest" in the eq offering.

The Houston-based company said terday that it had accepted bids fo small, profitable banks from sev buyers. Mr. Brown said the buyers wil identified early next month, after de tive sale agreements are signed. The will leave the company with seven b and about $6 billion in assets, down its current $8.5 billion in assets.

Pitney Bowes Inc.

Pitney Bowes Inc. said third-qu earnings rose 15%, largely reflecting increase in sales.

Net income rose to $83.2 million, cents a share, from $72 million, cents a share, in the year-earlier qua

The Stamford, Conn., company's ness-equipment segment, which co utes about 70% to revenue, posted increase in operating profit.

Revenue rose 5.7% to $861 million $813.9 million. Revenue included million from sales, a growth of 9%.

The company, a maker of bus equipment and supplies such as co facsimile and mailroom machines, sa mail processor, Paragon, introduc July in the U.S. made a good con tion to U.S. sales results.

"Internationally, sluggish reco conditions continued to hamper ou formance, particularly in the U.K.," mailing, sales and rentals decrea said George B. Harvey, chairma president. The decline, however, partly offset by increased service nue.

QUASI-ONE-DIMENSIONAL MODEL OF ELECTROCHEMICAL LOADING OF ISOTOPIC FUEL INTO A METAL

COLD FUSION

TECHNICAL NOTE

KEYWORDS: *cold fusion, isotope loading, deuterium*

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A quasi-one-dimensional model examines the electrochemical loading of isotopic fuel into a metal cathode. Both the competitive evolution of gas at that cathode and the ratio of the electric energy to thermal energy may control the spatial distribution and loading rate.

INTRODUCTION

In March 1989, electrochemically induced nuclear fusion reactions were reported[1,2] but were initially very difficult to reproduce. By 1992, several experiments had demonstrated that anomalous nuclear and enthalpic processes occur in palladium that has been highly loaded with deuterium.[3-5]

This technical note discusses the electrochemical loading of a palladium cathode with an isotopic fuel (deuterium). A quasi-one-dimensional model was developed that suggests that both competitive gas-evolving reactions at the metal surface and the ratio of the applied electric field energy to thermal energy ($k_B \times T$) appear to be decisive in controlling the loading of the metal by the isotopic fuel.

QUASI-ONE-DIMENSIONAL MODEL

Classically, an electrode in a heavy water solution at equilibrium should measure potentials associated with the Nernst equation. However, during the loading of isotopic fuel or during the fusion reaction, the system may not be at equilibrium. Furthermore, such derived solutions may be less informative regarding the rates of such loading or fusion reactions. Therefore, a quasi-one-dimensional model has been developed in an attempt to describe the flux of deuterons toward and into the cathode.

The application of an electric power source generates an applied electric field intensity. The problem of a mathematical solution includes the fact that the electric field is itself altered as the solution and system each respond with complex conduction and polarization phenomena.[6] The salient result, among other things, includes cation flux toward the cathode. There also results in the pericathodic solution a buildup of both deuterons and other cations, as well as the development of a low dielectric constant (gas bubble) layer. Ionic drift, secondary space-charge polarization, propagation of solvated deuterons, deuterons in clathrates, and intra- and intermolecular deuteron transfer in the heavy water,[7] and the formation of low dielectric constant (compared with water) bubbles abutting the cathode are the minimum expected.[8,9]

Figure 1 shows the direction of the applied electric field and its effect on the spatial distribution of deuterons in the aqueous solution and cathode. Figure 1 shows the four regions of the electrochemical cold fusion cell. The first region

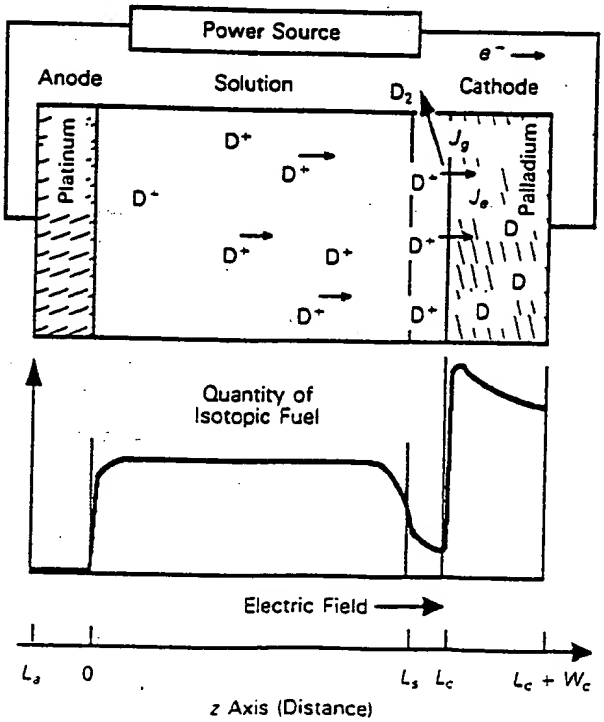

Fig. 1. Four-region cathode model.

is the platinum anode in which few deuterons reside. The second region is the solution, which is modeled as extending between $0 < z < L_c$. The third region is a double layer, whose width $L_c - L_s$ is greatly exaggerated in the figure. The last region is the palladium cathode, beginning at L_c and of width W_c. $L_c - L_s$ is so small that for most calculations, $z = L_c + L_s$ is simply taken as $z = L_c$.

Within the solution, the deuterons are distributed mainly tightly bound to oxygen atoms as heavy water. The drift induced by the applied electric field is shown schematically in Fig. 1; it does not mean that the deuterons actually are free to travel in such a simple fashion.

In this model, a double layer is present between the solution and the metal. The double layer is, in part, created by the cathode fall of ions and other polarization reactions of the solution and the solutes therein to the applied electric field. This boundary between the palladium cathode and the heavy water solution also may influence the loading rate of the metal by the isotopic fuel.

As Fig. 1 shows, at least three other deuteron fluxes must be considered. The model presented links the deuteron flux from the solution into the pericathodic volume, and then finally either into the metal or toward gas evolution. Not shown in Fig. 1 but considered in the model is the flux of deuterons lost in any and all putative fusion reactions (represented as J_f).

DEVELOPMENT OF THE QUALITATIVE MODEL

In the absence of solution convection, a quasi-one-dimensional model can be developed by considering that the flux J of any species (here the deuterons) results from both diffusion down concentration gradients and electrophoretic drift.[9] For simplicity, solution convection and the impact of other conduction/polarization components are ignored for this analysis. Note that (see Nomenclature on p. 300)

$$J_D(z,t) = -B \times \frac{d[D^+(z,t)]}{dz} - \mu \times [D^+(z,t)] \times \frac{d\Phi}{dz} , \quad (1)$$

where

B = diffusivity of deuterons in each respective region considered (cm^2/s)

μ = electrophoretic mobility ($cm^2/V \cdot s$).

For this model, both material inhomogeneities and the anisotropy of the lumped parameters are ignored. Within the palladium, for example, there are great differences in B throughout the metal, especially between the lattice and grain boundaries.

Three additional components of deuteron flux must be considered. The first is the entry of deuterons into the bulk of palladium that constitutes the cathode. That flux is described as J_e, the rate at which deuterons physically enter the palladium cathode. The second deuteron flux is that component lost at the cathode to gas evolution and is described here as J_g. These deuteron flux terms are assumed to be present only at $z = L_c$. The term J_f is the flux of deuterons lost to fusion, which is assumed to be zero in the solution.

Adding the additional deuteron fluxes yields

$$J_D(z,t) = -B \times \frac{d[D^+(z,t)]}{dz} - \mu \times [D^+(z,t)] \times \frac{d\Phi}{dz} - \sum J_i(z,t) , \quad (2)$$

where $\sum J_i$ is the sum of all deuteron fluxes at the cathodic surface and in the bulk metal and

$$\sum J_i(z,t) = (J_e + J_g) \times u_0(z - L_c, t) + J_f \times [u_{-1}(z - L_c, t) - u_{-1}[z - (L_c - W_c, t)]] , \quad (3)$$

where

u_0 = impulse function, located spatially at $z = L_c$

u_{-1} = step function; the superposition of two such step functions represents that the fusion flux may actually occur within the bulk of the metal.

Solution for the time rate of change in any given volume is thus determined by these fluxes. Gauss' theorem simplifies this to

$$\frac{d[D^+(z,t)]}{dt} = \left[B \times \frac{d^2(D^+)}{dz^2}\right] + \left[\mu \times (D^+) \times \frac{d^2\Phi}{dz^2}\right] + \left[\mu \times \frac{d\Phi}{dz} \times \frac{d(D^+)}{dz}\right] + \left[\frac{d(D^+)}{dz} \times \frac{dB}{dz}\right] + \left[(D^+) \times \frac{d\Phi}{dz} \times \frac{d\mu}{dz}\right] - \frac{d\sum J_i}{dz} . \quad (4)$$

For simplicity and to solve, a number of approximations can be made as follows:

1. The applied electric field intensity imposes a negligible energy [in relation to thermal energy at any molecular site of interest in the bulk solution (where the ratio of electrical to thermal energies is 10^{-4} to 10^{-6})]. Therefore, no free charge density in the solution is expected. Thus, the Laplacian of the electric potential [and thus the second term on the right side of Eq. (4)] is zero. This assumption may not be correct either in the vicinity of irregularities (such as spikes) on the cathode or in the double layer (see below).

2. All of the fusion reactions are assumed to occur only at $z > L_c$ (i.e., no fusion occurs in the bulk solution).

3. Deuterium is neutral in charge and has insignificant electrophoretic mobility in comparison with that for D+. Deuterons also may migrate by dielectrophoretic forces[6] by way of D_2 and by way of both intra- and intermolecular deuteron transfer, but such effects are ignored in this simple model.

4. It is assumed that no recombination of any generated D_2 gas occurs to form heavy water. Thus, for simplicity, J_r (for recombination) is ignored.

5. Deuteron penetration is modeled to occur only at the cathode–double-layer boundary (at L_c), and such flux ($J_e + J_g$) is assumed to be electron limited, with an efficiency (electrical transferance) of η.

6. There is conservation of deuterons, with the exception of a small loss K_f to any fusion reactions. The value of K_f is extremely small compared with all other loading rates and/or gas-evolving reactions.

7. Neither solution convection, nor possible dielectrophoretic or other stabilization of that convection, is considered in this simple model.

8. Thermal effects are also ignored, but these could be especially significant across the double layer, especially in the

vicinity of irregularities such as spikes or near either temperature or material inhomogeneities.

Notwithstanding the foregoing, the steady-state general solutions are obtained by substituting

$$D^+(z) = \sum D_i \exp(\gamma \times z) , \quad (5)$$

where γ can be complex.

By substitution, collection of terms, and the use of the binomial expansion, the homogeneous solution of Eq. (3) becomes, in the heavy water solution, of the form $\gamma = \mu E/B$. The particular solution of the differential equation is "driven" by the sum of the deuteron fluxes toward fusion, into gas, and into the metal cathode, where $\sum J_i = J_f + J_g + J_e$.

A simple solution can be developed with further approximations and linearizations.

9. It is assumed that there is no spatial gradient to the diffusion coefficient of deuterons B and/or their electrophoretic mobility μ. This is not true within the palladium cathode and is probably not true across the double layer. However, this approximation does permit a more simplified expression.

10. The generation of D_2 gas, the fusion loss of deuterons by the putative fusion reactions, and the loading of palladium are modeled to occur as first-order reaction rates proportional to the local concentration of deuterons. This is probably not true for gas evolution because it involves the formation of diatomic deuterium, and possibly not true for some of the putative fusion reactions.

11. Terms K_g and K_e are assumed to be zero away from the surface of the cathode in the solution. The only contribution to the spatial derivative of the first-order deuteron flux rates is thus proportional to the absolute value of K_f, K_g, and K_e at that cathodic location. Note that

$$J_f = K_f \times (D^+) , \quad (6a)$$

$$J_g = K_g \times (D^+) , \quad (6b)$$

and

$$J_e = K_e \times (D^+) . \quad (6c)$$

For $0 < z < L_s$, the general solutions are thus

$$\gamma = 0, \left(\frac{qE}{2k_BT}\right) - \left(\frac{\sum K_i}{2B}\right) \pm \left\{\left(\frac{qE}{2k_BT} - \frac{\sum K_i}{2B}\right)^2 - \left[\left(\frac{1}{B}\right) \times \left(\frac{d\sum K_i}{dz}\right)\right]\right\}^{1/2} . \quad (7)$$

BOUNDARY CONDITIONS

The actual coefficients of Eq. (5) are determined both by the boundary conditions and by conservation of mass. The condition of mass conservation of all deuterons at some time T requires

$$\int_0^{L_c+W_c} A \times [D^+(z,t)]\, dz = \int_{-L_e}^{L_c+W_c} A \times [D^+(z,0)]\, dz - \int_0^T A \times \sum J_i(\tau)\, d\tau . \quad (8)$$

It is obvious that $D^+(t = 0)$ may not be uniform and that J_f, J_e, and J_g may not be time invariant. Furthermore, J_r and the possible addition of more deuterons to the system are also both ignored in this qualitative model.

The molecular flux at each electrode must be considered so that just at the palladium cathode $z = L_c$,

$$J_D(L_c,t) = J_e + J_g . \quad (9)$$

Deuteron entry to the cathode is assumed to be electron limited (with all entry occurring only at the cathode–double-layer interface), and so

$$\sum J_i(L_c,t) = J_e + J_g = \frac{\eta \times I}{A \times F} . \quad (10)$$

Finally, it can be assumed that there is a negligible number of deuterons at the anode. This is reasonable because of the unstable nature of cationic deuterons at that location, where the anode is the site of oxidation. The applied electric field intensity would sweep the palladium cations away from the anode toward that cathode. The assumption is also reasonable because of the low solubility of deuterons for platinum. Note that

$$[D^+(0,t)] = 0 . \quad (11)$$

The steady-state expression for the initial coefficient of the final spatial distribution at the pericathodic interface is proportional to

$$\frac{\langle D_i \rangle \times \left(\frac{qE}{2k_BT} - \frac{\sum K_i}{2B}\right) \times L_c}{\left\{\exp\left[\left(\frac{qE}{2k_BT} - \frac{\sum K_i}{2B}\right) \times L_c\right] + \left(\frac{qE}{2k_BT} - \frac{\sum K_i}{2B}\right) \times (L_c) - 1\right\}} . \quad (12)$$

L'Hospital's rule may be used to determine the initial coefficient in the limit as either K_e, K_g, or K_f approaches infinity. That limit is 1.

POSSIBILITY OF A CRITICAL LOADING FLUX

Examination of Eq. (7) reveals that there may be a critical loading rate that occurs when the terms in the parentheses in Eqs. (7) and (12) go to zero. That occurs at $L = L_c$ when

$$K_e = (\mu \times E) - (K_g + K_f) . \quad (13)$$

One implication is that the evolution of D_2 gas and loading of the palladium cathode are mutually exclusive. Another is that the critical loading rate appears to be related to the difference between the deuteron availability (secondarily produced by the applied electric field) and the loss of deuterons by gas evolution, loading of the metal, and the fusion reactions.

In fact, the ratio can be examined for its relation to thermal processes by substituting the Einstein relation:

$$\frac{B}{\mu} = \frac{k_BT}{q} . \quad (14)$$

At the beginning of an experiment involving the electrochemical loading of deuterium into palladium, J_f is zero because the palladium is not loaded. Therefore, the loading flux of deuterons into the palladium cathode is

$$J_e = \left(\frac{2B \times L_c \times \lambda}{\lambda + 1}\right) \times \langle D_i \rangle \times \left(\frac{1}{\left\{1 - \left[\exp\left(\frac{-qE \times L_c}{k_B T}\right)\right]\right\}}\right) \times \left(\frac{qE}{k_B T}\right)^2 , \quad (15)$$

where

$\langle D_i \rangle$ = initial concentration of deuterons in the solution

λ = relative loading rate, the ratio of the fluxes, loading flux J_e to the gas evolution flux J_g.

Note that

$$\lambda = \frac{J_e}{J_g} . \quad (16)$$

Thus, if λ is 0.01, most of the current goes to gas electrolysis, whereas $\lambda = 100$ would indicate a most efficient loading rate.

The substitution of Eq. (14) into Eq. (13) reveals that the loading is determined by two terms. The first term is controlled by the ratio of the organizing of the deuterons (by the applied electric field) to the random thermal disorganization. The second term is the mutually exclusive loss of deuterons at the cathode through gas evolution, represented by J_g [Eq. (13)] or by the loading factor in Eq. (16).

Figure 2 shows this relationship by plotting the relative loading of isotopic fuel into a metal based on the qualitative quasi-one-dimensional model described here. The loading flux of deuterons into the palladium at the cathode surface J_e is shown as a function of the electric field intensity parametrically for various rates of gas (D_2) evolution rates at the cathode (and resulting from J_g). The series of curves indicates that the loading rates may be critically dependent on the electric field energy as well as the competing gas-evolving reactions.

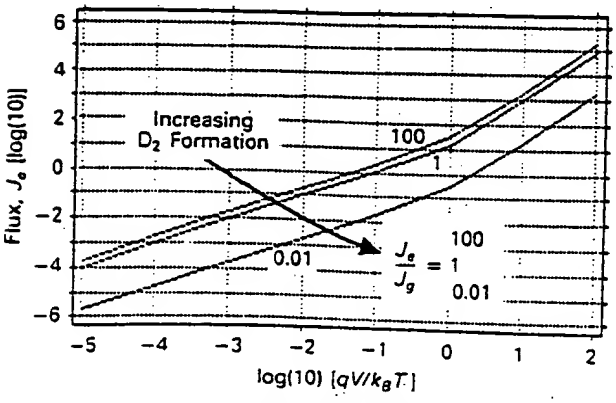

Fig. 2. Loading rate of palladium.

WITHIN THE CATHODE

Intermolecular deuteron transfer from the solution to sites within the palladium may dominate the rate of loading. Within the metal and across the double layer, the diffusion has been considered by several models. Defects, grain-boundary dislocations, and fissures may greatly influence the deep loading of the metal, and "zeolite"-like diffusion has been described.[10]

POSSIBLE IMPLICATIONS REGARDING SPIKES ON THE CATHODE

A corollary is obtained by inverting the equation, which indicates that the electric field must be greater than

$$E > \frac{\sum J_i}{\mu \times \langle D_i \rangle \times \left[2 + \left(\frac{\sum J_i \times L_c}{2B \times \langle D_i \rangle}\right)\right]} . \quad (17)$$

One interpretation is that spikes and irregularities on the cathode may be crucial to obtain adequate filling of the cathode. This effect may occur by way of the large electric fields that occur at such sharp points on a metallic surface such as the palladium cathode.

STEADY-STATE FUSION RATES

When the filling of the palladium with deuterium is complete, a "steady state" (to the degree such might exist) of fusion might be expected. At that time because the electrode is already fully loaded, then J_e would be expected to be small and J_f to be relatively more significant. J_e would be on the order of J_f, and so at that time,

$$J_f = \frac{B \times L_c \times \langle D_i \rangle}{\left[1 - \exp\left(\frac{-qE \times L_c}{k_B T}\right)\right]} \times \left(\frac{qE}{k_B T}\right)^2 - \frac{J_g}{2} \quad (18a)$$

or

$$J_f = \left(\frac{2\lambda}{2\lambda + 1}\right) \times \left(\frac{B \times \langle D_i \rangle}{L_c}\right) \times \left[\frac{1}{1 - \exp\left(\frac{qV}{k_B T}\right)}\right] \times \left(\frac{qV}{k_B T}\right)^2 . \quad (18b)$$

Equation (18a) uses the two deuteron fluxes at the cathode to define the approximate fusion flux. Equation (18b) substitutes the transolution voltage, and thereby assumes a simple distribution, neglects contact potentials and overvoltages, and uses the simplication of λ as the relative loading rate factor. The Einstein relation is used to put the equation back in terms of the original parameters.

POSSIBLE IMPLICATIONS FOR CODEPOSITION AND OTHER THEORIES

Because palladium cations in solution can be modeled similarly to deuterons (with the exception of intra- and intermolecular deuteron transfer and their different roles in clathrates), such palladium nuclei will also drift toward the cathode in an applied electric field. For palladium, there is

obviously no K_g or K_f term, but K_e does exist, and the palladium cations can electrodeposit on the cathode. The model was examined to consider this further. Coupled equations, considering both charge carriers, were used to determine the final distribution of deuteron species in the bulk solution. An equation similar to Eq. (12) was used to determine the ratio of deuterons to palladium just at L_c. This is the local loading ratio.

The derivations for the spatial distribution of palladium nuclei undergoing codeposition from the solution indicate that the physical deuterium/palladium ratio near the cathode surface is significant and nonzero shortly after the electric field is applied to the solution.

The model indicates that the distribution of codeposited palladium and deuterons onto the cathode should theoretically yield excess energy more quickly than simple electrodeposition of deuterons onto palladium. This advantage accrues because a local high fractional saturation of the deposited phase occurs at L_c. This analysis indicates that the active medium would be very close to fully charged as it is created, enabling it to function immediately.

In cold fusion experiments, full loading appears to be a prerequisite, but possibly insufficient requirement, before fusion occurs. Therefore, as compared with simple electrodeposition of deuterium onto a palladium cathode, codeposition may surmount at least one rate-determining step.

Finally, some theories of cold fusion are reported to involve the putative requirement of a pericathodic or intracathodic role for second-row elements during the fusion reactions.[11] This quasi-one-dimensional model could be used to similarly determine both their buildup and loading parameters.

SUMMARY

A simple qualitative quasi-one-dimensional model is derived to consider the loading of deuterium into palladium. Both competitive gas-evolving reactions at the metal surface and the ratio of the applied electric energy to thermal disordering energy ($k_B \times T$) may be decisive in controlling the loading of the metal by the deuterons obtained from heavy water. There appear to be possible implications for the shape of the cathode and for codeposition methods of loading the cathode.

NOMENCLATURE

A = area

B = diffusivity of deuterons (cm^2/s)

$(D)tot$ = total deuteron concentration (used within the metal)

$(D+)$ = deuteron concentration (used within the solution)

$D[t = 0]$ = initial deuteron concentration (at time $t = 0$)

E = electric field

F = Faraday

I = electrical current

J_D = flux of deuterons in solution

J_e = flux of deuterons entering into the palladium cathode

J_f = flux of deuterons lost in putative fusion reaction(s)

J_g = flux of deuterons at the cathode evolving to gas

K_e = first-order deuteron entry rate

K_f = first-order deuteron fusion rate

K_g = first-order deuteron gas evolution rate

k_B = Boltzmann constant

L = length

q = electric charge

T = absolute temperature (K)

V = transsample voltage

z = distance variable

Greek

ϕ = potential

μ = electrophoretic mobility ($cm^2/V \cdot s$)

η = electrical transference ratio

λ = relative loading rate

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NUCLEAR FUSION IN AN ATOMIC LATTICE : AN UPDATE ON THE INTERNATIONAL STATUS OF COLD FUSION RESEARCH

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BIPHASIC BEHAVIOR IN THERMAL ELECTROLYTIC GENERATORS USING NICKEL CATHODES

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ABSTRACT

Thermal spectroscopy, with attention to background noise, enables accurate determination of sample activity and has revealed a biphasic behavior to the generated excess heat. Nickel cathodes (using ohmic thermal and other metallic cathodic controls) were examined versus either platinum or gold anodes in light water systems. The peak power amplification [$\Pi_{OUT}/\Pi_{IN} = \Pi_{Ni}$] was in the range of ~2.27 (+/-1.02). Peak power outputs have been in excess of 2 watts, with power densities (nickel) of more than ~7 (+/-4.3) watts/cm^3. There may be several reasons for the biphasic effect. The origin of the site of the heat shifts at different locations within the π-notch.

keywords: excess heat, nickel electrolysis systems, calorimetry, biphasic response

INTRODUCTION

Since March 1989, cold fusion has been confirmed both for heavy-water electrolytic systems with palladium cathodes and lithium salts [Fleischmann, Pons (1989), Fleischmann et alia (1990), Fleischmann & Pons (1992), Fleischmann & Pons (1993), Miles et alia (1993) Miles, Bush (1994), Will et alia (1993), Storms (1990), Will et alia (1994)] and for light-water electrolytic systems with nickel cathodes and various electrolytes [Mills, Kneizys (1991), Bush, Eagleton (1994), Noninski (1991), Notoya et alia (1993), Notoya (1994), Matsumoto (1990), Matsumoto (1993), Ohmori et alia (1993), Srinivasan et alia (1992), Swartz (1996a), and Swartz (1997a)].

Consistent with a possible nuclear origin for the observed excess heats, there have been demonstrations of both helium-4 [Miles et alia (1993), Miles, Bush (1994)] and tritium [Will et alia (1993), Storms, Talcott (1990), Will et alia (1994), Bush, Eagleton (1994), Notoya (1994), Srinivasan et alia (1992)] as nuclear ash, the former linked with the excess heat. There have also been improvements in calorimetric analysis [Melich & Hansen (1993), Swartz (1996c), Swartz (1994b), Swartz (1997b)], definitions of input power [Swartz (1996d)], and better thermal power spectroscopy [Swartz (1997a)] which have together enabled more accurate determinations of activity of select loaded materials (Figures 1,2). The thermal power spectrograms have also revealed a biphasic character to the excess heat when examined as a function of input driving power (Figures 3,4).

Sample Activity Defines The Power Ratio

Figure 1 shows a thermal power spectrogram, including the background noise for an electrolytic light water generator containing two paired platinum anodes run in sequence versus a spiral nickel cathode (Swartz 1997a). Thermal (ohmic) controls are shown for comparison both before, and between, the two generator pulses. Figure 2 shows another thermal power spectrogram for a generator with a gold anode and a cluster of nickel cathodes [ordinary water (H_2O)]. Both the input, and output, power and energies [the step-like curves read off the right y-axis] of the calorimeter are shown. The input and measured output powers have a logarithmic scale (left y-axis). These nickel light water generators were characterized by excess heats beyond the electrical input energies, in contrast to the ohmic controls. There was no subtraction in the calculated electrical input power for the thermoneutral potential as so recombination is not an issue. For the nickel spiral cathodes with platinum foil anodes, the peak power amplification [$P_{OUT}/P_{IN} = \Pi_{Ni}$] were in the range of 2.27 (+/-1.02). Peak power outputs have been in excess of 2 watts, with power densities (nickel) of more than 7 (+/- 4.3) watts/cm^3.

Biphasic Response

An optimum "notch" or peak is observed in the curve of power gain versus power input (watts) or current (amperes) under those conditions which enable the generation of excess heat. At the notch, the peak power ratio (π_{Ni}) of 2.5 to 3 was

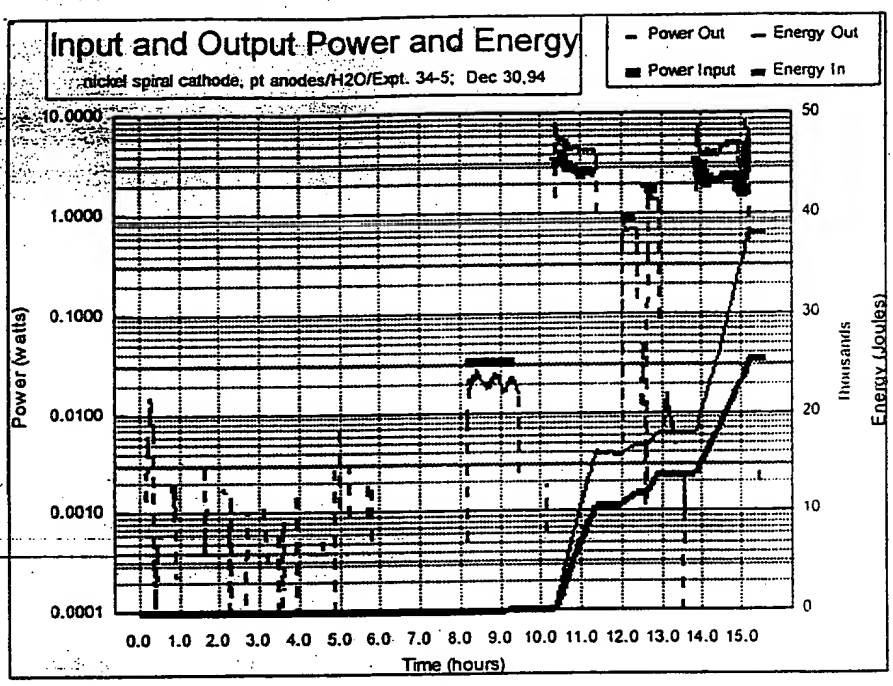

FIGURE 1 - THERMAL SPECTROSCOPY OF NICKEL LIGHT WATER ELECTROLYTIC SYSTEMS

A nickel light water system using platinum anode. The input and output power and energies of a platinum foil anode (area 4.0 cm^2) and spiral nickel cathode (area 4.8 cm^2, volume 0.059 cm^3) in ordinary light water [H_2O]. The step-like functions are the energy curves [read off the right y-axis]. The powers (thermal background, input, output) are the remainder of the curves and have a logarithmic scale (left y-axis). To the lower left, thermal noise is shown (background for this experiment) ranging from ~20 to a few milliwatts. The first input (control) pulse is at ~8 hours. The first, third, and fourth input pulses are the controls.

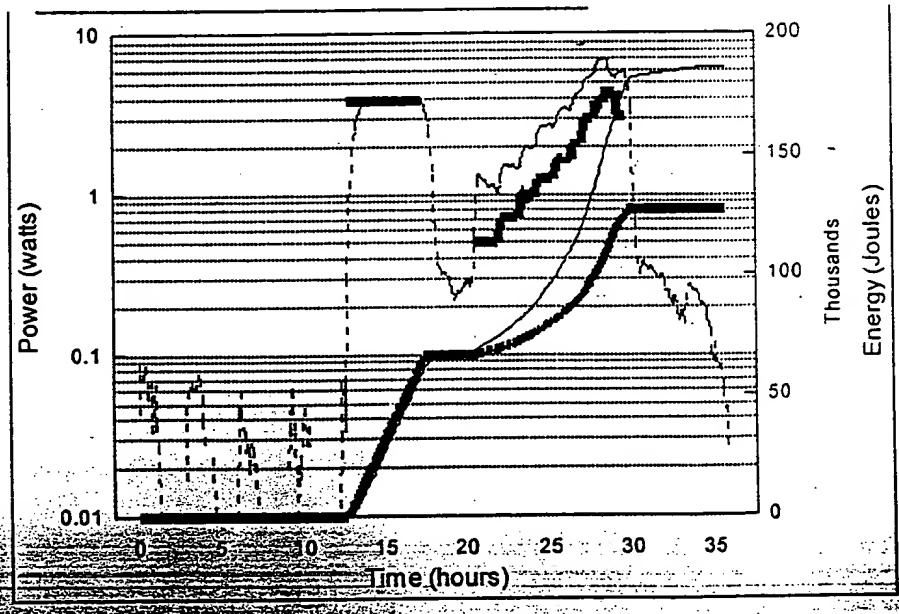

FIGURE 2 - THERMAL SPECTROSCOPY OF NICKEL LIGHT WATER ELECTROLYTIC SYSTEMS

A nickel light water system using multiple nickel cathodes and gold anode. Six spiral nickel cathodes (combined cathodic area 28 cm^2, volume 0.35 cm^3) were used. To the lower left is shown thermal noise (background for this experiment) ranging from 90 to 60 milliwatts and extending until the first input (control) pulse at about 12 hours.

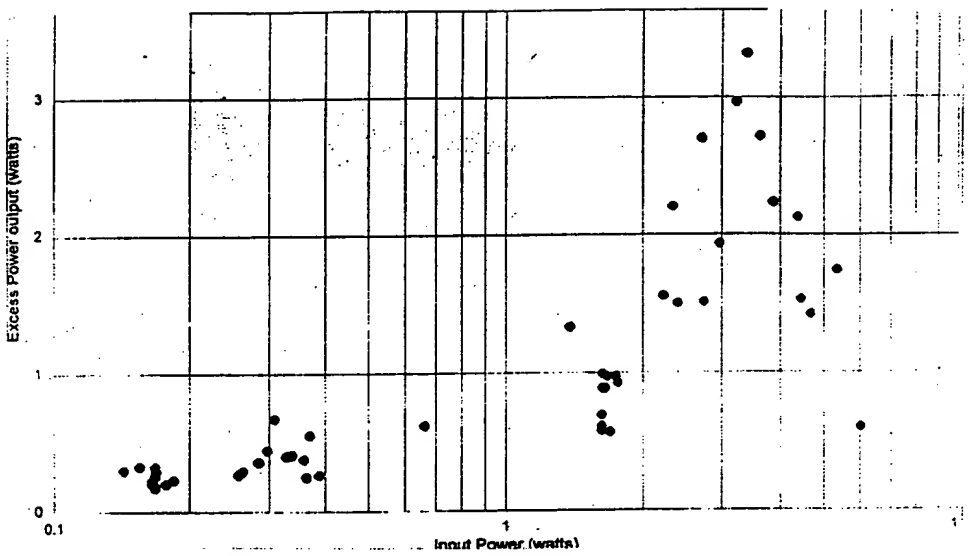

FIGURE 3 - THE BIPHASIC NATURE OF EXCESS HEAT AS A FUNCTION OF INPUT POWER

The biphasic character of excess power [watts] as a function of applied input power (logarithmic axis). Nickel spiral cathode versus platinum anode, light water. In this experiment two platinum foil anodes (area 8.0 cm^2) were used with a centrally placed nickel cathode (area 4.8 cm^2, volume 0.059 cm^3) in light water [H_2O].

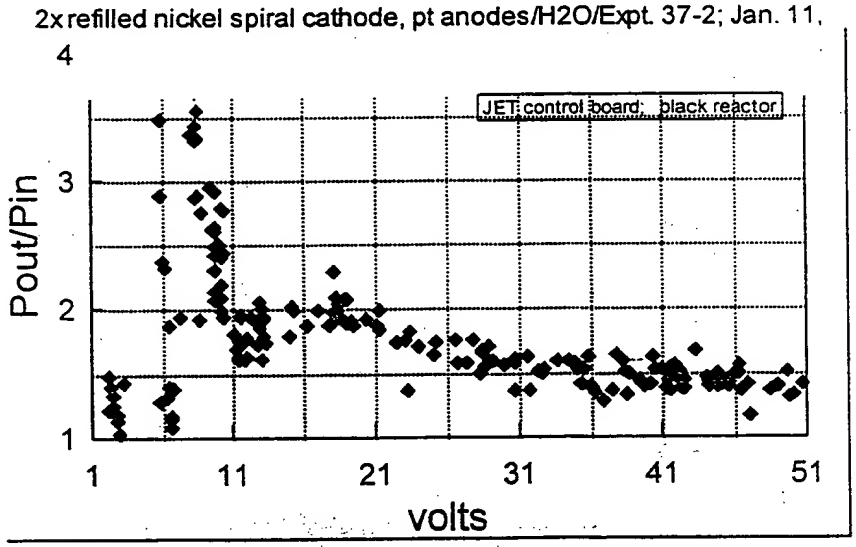

FIGURE 4 - THE BIPHASIC NATURE OF EXCESS HEAT (POWER AMPLIFICATION FACTOR) AS A FUNCTION OF INPUT VOLTAGE

The biphasic character of power amplification [$\pi_{Ni} = P_{out}/P_{in}$] as a function of applied transsample potential using a single platinum foil anode (area 4.0 cm^2) and spiral nickel cathode.

typical with a falloff under increasing input power or current levels towards a ratio of 1. Figure 3 shows the biphasic character of both the excess power (watts; P_{out} - P_{in}) as a function of input power. Figure 4 is from another experiment and shows the biphasic character of the power amplification factor [π_{Ni} (nondimensional) defined as P_{out}/P_{in}] as a function of input (transsample) voltage. The resulting biphasic behavior of the excess heat is important because -- combined with the now well-known problems of achieving adequate loading of properly prepared suitable electrode materials -- it may account for some of the widespread difficulties in observing the phenomena. This failure to reproduce the cold fusion phenomena may have occured because those experimental systems may have been inadvertantly driven outside of the π-notch manifold. The remainder of the 'negative' experiments may have had insufficient loading, and thus were also conducted in a region outside of the "notch".

Although this does not explain how successful achievement of these reactions occur, it may begin to explain when they will not occur; namely by driving the electrode in a region outside of the π-notch manifold.

ETIOLOGY OF THE BIPHASIC NOTCH

Thus, although the phenomena described by cold fusion researchers do appear to be real, there are now several reasons known for the difficulty in achieving the desired reactions. In addition to purity of material, we believe that part of the difficulty is related to the π-notch behavior, and that the Q1D (quasi-1-dimensional) model of isotope loading into the Group VIII metal electrode appears to explain much of the biphasic effects. Briefly, the slow rise of excess power output observed from zero input power to the peak which is observed is hypothesized to probably be due to loading of the metal electrode with the much lower weight hydrogen isotope. The falloff beyond the peak output for higher input drive levels may be due to competition of loading with electrolysis and other factors. The following is a summary of the formal derivation.

The Initial Portion

Many "negative" results in the field of fusion from isotopic fuel in a material may be in part due to inadequate loading of the low atomic weight isotope (deuterium) into the Group VIII transition metal (palladium) lattice. Materials such as palladium must physically absorb enough deuterium to obtain the desired reactions. Although most of the isotopic material of interest fails to enter the metal, there has been insufficient (or no) mention of the amount of filling (loading) achieved in most "negative result" studies in this field. However, the loading of the isotopic fuel from the solution to the metal greatly influences the outcome.

The Peak Region

Both the sample's initial activity, and how it is actually "driven" effect its actual output. The peak activity of any given sample [Π_{max}] varies from each individual piece to piece. It also may be dependent upon the samples preparation, connection, and history [Swartz (1994b), Swartz (1997b)]. We believe that each sample generally has an actual measured power gain (π) lower than Π_{max}. To observe the samples maximum gain, Π_{max}, requires that the sample must be "driven" in the correct fashion. Thus, the actual observed power gain [π] of each sample mathematically described is that peak factor diminished by the failure to optimally drive the sample[11]. The second factor in the power gain equation (eq. 1), δ, is less than unity.

$$\pi \text{ (power gain factor)} = \Pi_{max} * \delta \qquad \text{(eq. 1)}$$

The Falloff Region

Classical calculations of the electrochemical activities of an ionic electrolyte located next to a metal electrode [Uhlig (1971), Bockris (1970)] could be applied to cold fusion reactions. However, during and following the loading of the isotopic fuel into the metal electrodes the systems may not actually be at equilibrium [Swartz (1992)]. Other methods were examined to derive the distributions of deuterium in the palladium and the solution.

QUASI-1-DIMENSIONAL MODEL OF LOADING

Therefore, a quasi-one-dimensional model for an electrode filled by the isotopic fuel was formulated which has enabled the pericathodic deposition of ions to be investigated using non-equilibrium calculations [Swartz (1992)]. Furthermore, other insights were obtained from the model. Because not all of the isotopic material (deuterons from the solution around the elctrode) enters the metal, the loading flux into the bulk volume must be distinguished from the gas evolving flux. The Q1D model of isotopic loading utilizes the isotope flux equation (equation 2) which considers the differential isotope diffusivity (B_D), electrophoretic mobility (μ_D), inhomogeneous spatial distribution ([D(z,t)]), solubilities and magnetic susceptibilities. Without significant convection, the flux (J_i) of any i_{th} species (here deuterons) results from diffusion down concentration gradients and electrophoretic drift [Melcher 1981, Swartz 1992].

$$J_D = -B_D * \frac{d[D(z,t)]}{dz} - \mu_D * [D(z,t)] * \frac{d\Phi}{dz} \qquad \text{(eq. 2)}$$

Coupled Differential Equations

There follows coupled differential equations for each of the deuteron fluxes at the cathode, and for all cations in solution. With only consideration of the deuteron flux, the first flux component at the electrode surface is the entry of deuterons into the bulk of palladium (J_1). The second flux component is the volume loss of deuterons secondary to gas evolution (J_2). The mathematical solutions are determined both by the boundary conditions and by conservation of mass. The Q1D model has revealed information about the relationship between

the loading and the competitive gas-evolving reactions at the surfaces of the electrode [Swartz (1994d), Swartz (1997a), Swartz (1997c)]. The ratio of the applied electric field energy to thermal energy [k_B*T] is decisive in controlling the loading in palladium and may be applicable to nickel and the proton reactions (or deuteron) at a nickel surface or in its volume.

Competition Between Loading And Gas Formation

The Q1D model of isotope loading indicates that the deuteron first order loading rate into the electrode is critically linked to gas evolution and is first order on $\mu_D * E$. This first order loading rate equation (equation 3) relates the deuteron availability (secondary to the applied electric field) to the losses of deuterons to both gas evolution (κ_g) and the fusion reactions (κ_{fus}).

$$\kappa_e = (\mu_D * E) - (\kappa_g + \kappa_{fus}) \qquad \text{(eq. 3)}$$

One simple but important corollary of this derivation is that the evolution of diatomic deuterium (D_2) gas and deuteron loading to the palladium cathode are mutually exclusive for any given applied electric field. The interpretation is that there is a fixed rate of excess heat available. With increasing drive input, the efficiency must therefore decrease, as is observed. There may be other reasons, however, for the biphasic effects ranging from variations in the flux loading rate ratio to non-linear effects due to low dielectric constant layers in front of the electrode.

Location Of Excess Heat Within The π-Notch

The origin of the site of heat may differ at different drive levels along the biphasic response curve. We have examined electrode temperatures *in situ* using a system which is relatively unaffected by the local electrical conditions. Because of potential errors associated with flow calorimetric systems [Swartz (1996b), Swartz (1996b)], a static isoperibolic calorimeter with waveform reconstruction and thermal controls [Swartz (1997a, 1997d)] was used. The temperature probes were specialized for this environment. Probes were positioned abutting the central portion of the nickel spiral cathode, the platinum anode plate, and at several locations in solution.

For nickel-platinum-light water systems, the site of peak heat appears to change as the system is driven with increasing electrical drive. Although it is generally assumed that the excess heat liberation occurs at the cathode, in this system the site of peak temperature release was observed to be at the cathode only in when the system was driven in the center of the π-notch. This was not necessarily true at other locations in the operating drive space. At the lowest electrical drive levels, there appeared to be roughly equal amounts of heat generation (under-unity) at both the anode and cathode. This might be consistent with the desired reactions not occurring at the lowest electrical drive levels, or with loading failures as discussed above, and described in the quasi-one-dimensional model of isotope loading. Near the peak of the π-notch, the cathode (nickel) appears to be the site of maximum heat generation and in over-unity amounts within the electrochemical cell. Furthermore, it is only at the peak that this outstanding cathodic behavior occurs. This dichotomy of temperature between the two electrodes occured despite the excellent thermal conductivity of water. It is at the highest electrical drive levels, outside of the π-notch where the excess heat falls-off, that there then appeared to be more heat output generation (decreasing toward under-unity amounts) coming from the anode. This incremental increase of anodic heat at these higher drive levels could be consistent with some increasing component of recombination occurring at that location.

SUMMARY

Thermal power spectroscopy, with attention to background noise, enables accurate determination of sample activity and has revealed a biphasic character to generation of the observed excess heat. The latter is also important because it may account for some of the widespread difficulties in observing the phenomena.

At the π-notch, the peak power ratio (π_{Ni}) for these light water electrolytic nickel cathodic systems was in the range of 2.5 to 3. There was a typical falloff of the observed power ratio for increasing input power or current levels, with a decrease towards a power gain ratio of 1. There may more than one reason for this biphasic effect. The Q1D (quasi-1-dimensional) model of isotope loading explains the biphasic effects in terms of loading and competition of the loading with electrolysis. The notch may also be dependent upon the sample's preparation, connection, and history, or failure to optimally drive the sample. Furthermore, the samples may have a peak output which is then only diluted by further increasing electrical power inpout.

The origin of the site of the heat appears to change at different drive levels. In nickel light water systems, under the π-notch where there is excess heat, the cathode is incrementally hotter than the anode. Beyond the π-notch, as the excess heat appears to decrease as input energy is wasted with the electrical energy creating more electrolysis, the anode becomes relatively hotter, probably consistent with recombination at that site.

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Features

Departments

Cold Fusion and the Press

by Charles G. Beaudette, 1993 Paxton Lectureship Winner

New developments in science have always held my attention. Beginning with my undergraduate days at MIT, I have followed them at a fairly technical level and I have continued to do so during 32 years of engineering practice. When something seems wrong I am apt to speak up, or write down, as the case may be. And so it is with this matter of cold fusion.

To be fortunate enough to have an audience of those of professional achievement makes my task more pleasurable as it authorizes me to tackle the subject more aggressively and more definitively. Should this field develop rapidly, it may well impinge on your professional lives more quickly than you might ordinarily expect.

Although I am attracted to the technical story of cold fusion, my interest is also piqued by the public assault upon its two discoverers. Assault, by or through the press, upon a newly emerged public figure has become a deplorable commonplace of our communal life. The two discoverers of cold fusion now live and work in France and are financed by a Japanese company. It has come to that.

Thomas S. Kuhn, in his book, *The Structure of Scientific Revolution*, makes this observation: "Normal science...often suppresses fundamental novelties because they are necessarily subversive of its basic commitments." Cold fusion is subversive of hot fusion, and it is moving right along. Visitors to MITI, the Japanese Ministry of International Trade and Industry, report that it will spend $25 million over several years in additional support of cold-fusion research of some 15 companies and several universities, and that it expects that the first prototype power packs using cold-fusion technology will be available no sooner than 1997 and no later than the year 2000.

Although this is a professional audience, I recognize that it is also a non-technical one. So let me first get out of the way a brief description of the cold nuclear fusion device that we will call the *cell*.

We start with a brief mention of *hydrogen*, the lightest element; it has only one proton in its nucleus. We will also be concerned with an isotope of hydrogen called *deuterium;* it is like hydrogen except that it has one proton and one neutron in its nucleus, so it is twice as heavy. When its one electron is stripped away, leaving just the nucleus, it is called a *deuteron*.

Heavy water is the name given to water whose molecules are made up of deuterium and oxygen. All water has some deuterium in it; a glass of water has many millions of water molecules made with deuterium instead of hydrogen.

Palladium is a precious metal with certain unique properties. It acts as a catalyst; it makes other things happen while not being itself consumed. A unique characteristic of palladium is that it can absorb large amounts of hydrogen. This has been known for more than half a century and is used as a method to purify hydrogen. It is for this special characteristic that palladium is used in the cold-fusion cell.

If you take a one-quart mason jar and fill it with heavy water, you have a good start on making a cold-fusion cell. Into this jar place the important electrode, a sheet of palladium metal an inch square or so with a wire connected to it coming out of the jar. Then place a platinum wire in the water and add a salt, such as lithium hydroxide, to make the water conductive.

If a direct current source is connected to the electrodes with minus on the palladium, the cathode, you have an electrolytic cell not unlike what many of you built in secondary school chemistry class. The action of the current through the solution will cause the water molecules to come apart chemically. Oxygen bubbles up from the platinum electrode, and hydrogen or deuterium gas bubbles up from the palladium electrode.

In March 1989, two electrochemists, Stanley Pons and Martin Fleischmann, at the University of Utah, Salt Lake City, where Pons was head of the chemistry department, announced at a press conference that they had generated heat in an electrolytic cell by means of a cold nuclear fusion reaction.

In the Pons and Fleischmann electrolytic cell, as it was explained by them, the electrical current pulls deuterium atoms into the atomic structure of the palladium electrode. There the deuterium atom finds a place of its own, and if its electron blends in with other electrons in the metal, only the deuteron—the nucleus—remains.

It is argued that nuclear fusion takes place among the deuterons, and maybe among the deuterons and protons, within the metal lattice of palladium atoms. The fusion action releases heat energy into the metal and then into the bath. This heat adds to the heat caused by the original electric current. This increase of heat is referred to by scientists working on these cells as "excess energy."

The law of conservation of energy states that, in principle, every minute erg of energy can be fully accounted for. With energy traveling about, as it does, by conduction, convection and radiation, an accounting for every tiny bit can be difficult in practice. Should an experiment release much more energy, atom for atom, than is possible from any chemical reaction, that would be an indication that the energy is coming from the nucleus, and that further scientific investigations are warranted.

To understand the ensuing controversy it is important to remember the grounds upon which the claim of fusion is based. The claim of cold fusion by Pons and Fleischmann and other scientists is based upon the generation of excess heat at a density that cannot be explained by any process other than a nuclear reaction.

Science is built on the repeatable experiment. Therefore, we should ask, *Is the Pons and Fleischmann experiment repeatable?*

Yes and no; the cold-fusion experiment is immature. Many have repeated it in that they demonstrably have obtained excess energy. That everyone could not repeat the experiment means that its de-

sign is yet only partially understood. Is an immature experiment science? All revolutionary experiments had to go through a process of creation and development until they were perfected. Of course such work is science. But in retrospect, it seems clear that it all looked much easier than it was, and, surprisingly, it still does.

Michael C. H. McKubre, at Stanford Research Institute, demonstrated excess energy in Pons and Fleischmann-type cells during the fall of 1991, and most recently Akito Takahashi of Osaka University also did. These results have been published in refereed scientific journals. During the past three years the repeatability of the Pons and Fleischmann cell experiment has been improving steadily while the experiment has been maturing.

The latest experimental work aims to improve the specification of the palladium electrode and obtain sufficient infusion of deuterium into the palladium. It is now accepted that to make the cold-fusion process begin functioning it is necessary to achieve a "loading" of almost one deuterium atom for each atom of palladium. Some recent experimenters have managed to "load" into the metal more than one deuterium atom for each atom of palladium.

To share such experimental knowledge from India, Italy, the United States and Japan, the First Annual Cold Fusion Conference was held in Utah in the spring of 1990, followed by a second one in June 1991 in Como, Italy. The third was held last fall in Nagoya, Japan, and the next will be held in Hawaii this December.

You may be aware that in 1989 the State of Utah committed $5 million to support further research. As part of the oversight of this expenditure the legislature commissioned Prof. Wilford F. Hansen, physicist at the University of Utah, to analyze the raw data that Pons and Fleischmann gathered from some of their performing cells. After doing extensive analysis of the data, Hansen concluded in June 1991 that, for one particular cell, "This [excess heat] is already an order of magnitude [10 times] larger than the energy [needed] to vaporize the entire palladium electrode. We have thought of no other self-consistent explanation than that the excess heat is real and very significant." For another cell, he reports, "The integrated excess heat is about 1700 EV [electron volts] of energy per palladium atom. This is about 400 times the vaporization energy of palladium...Therefore, [this cell] appears to be producing large amounts of excess heat, with the amount increasing with temperature."

Prof. Akito Takahashi, of the Department of Nuclear Engineering, Osaka University, Japan, lectured at MIT in the spring of 1992 describing his most recent excess-energy results.

> Total energy balance for the 1 week + 2 months run was...total input energy = 250 mega-joules, total output energy = 410 mega-joules and net excess heat = 160 mega-joules...average input power = 50 watts, average output power = 85 watts and average excess power = 35 watts...We should have, therefore, [a]'hidden' excess heat source in the cell. Other possible heat sources by chemical reactions can be estimated as too small to explain observed excess heat;...chemical reactions...can produce heat level[s] of the order of 0.015 mega-joules. The order of excess heat observed is about 1000 times greater than chemical heat sources.

More recently, Pons and Fleischmann report that high levels of heat production are now 100 percent reproducible and demonstrate a cell with an input power of only 37 watts that can boil away 1/20th of a liter of heavy water in 10 minutes. This feat requires an excess power level of 144 watts during the 10 minutes.

From this variety of evidence and argument, what may we reasonably conclude?

The law of conservation of energy is considered absolute by all parties to the cold-fusion controversy. The excess energy absolutely must have an ultimately identifiable source. There is no escape from this imperative. This quest is the very stuff of authentic scientific exploration regardless of where the answer resides. Excess energy from the cold-fusion experiment is proved but not explained.

No one has any suggestion as to an alternate source of the observed excess energy other than the Pons and Fleischmann conclusion that some species of fusion process takes place within the atomic lattice structure of the palladium electrode.

It is for this reason that the experimental and theoretical work that passes under the name of cold fusion is a thoroughly legitimate scientific activity and deserves to be funded.

Let's see then, how the critics approach the matter of cold fusion.

Of the five books now available on this subject, the two that are most critical entirely avoid the implications of excess energy. Neither of them tells the reader that excess energy has been well confirmed, that its magnitude is beyond chemical sources, nor offers the author's opinion of its significance.

Then the critics look for evidence of nuclear reactions—nuclear ash—that are generated by nuclear processes. Physicists and chemists with extended experience in the nuclear field, naturally enough, rummaged through the experimental data looking for fusion's familiar neutrons and gamma rays. Finding few or none of these, they have raised a hue and cry against cold fusion, saying that it isn't.

But this assumes that the heat-generating process in question is known. Certainly one can look for the products of those fusion processes that are recognized from other work, but that involves the assumption that nothing really very new is happening here. Such considerations are named "miracles" by Prof. Huizenga, the author of *Cold Fusion: The Scientific Fiasco of the Century*, as a way to rhetorically discredit their possibility.

The measurement of excess energy by many scientists is accurate, real and large. Also, no one—physicist, critic or scientific experimenter—even can suggest possible sources for this amount of energy other than a nuclear source. Therefore, we must anticipate the identification of new and now-unfamiliar nuclear reactions. This now seems to be the working assumption of those scientists leading the experimental work.

The criticisms leveled by those who did not see familiar nuclear emissions from the cells and who did not much care about something called excess energy are well documented.

Prof. Stephen E. Koonin, a respected physicist: "We have suffered enough from the delusions and incompetence of Pons and Fleischmann."

Prof. Ronald Parker, Director of the MIT Plasma Fusion Center, said that the work of Pons and Fleischmann is "scientific schlock" and "maybe fraud."

Prof. John R. Huizenga, University of Rochester, said that cold fusion is "pathological science."

This last phrase appeared in an October 1989 report by the U.S. Department of Energy Cold Fusion Panel of the Energy Research and Advisory Board. The report recommended no money for cold-fusion research and prohibited any such research activities in Department of Energy laboratories. Notice the severity of this report. By administrative fiat, some of our finest scientists—directors of federally funded laboratories—are not permitted to carry on cold fusion experiments with discretionary funds. This prohibition is probably the principal factor in preventing an expansion of cold-fusion research studies in the United States.

And the critics continued. Physics professor H.W. Lewis said, "That they lived to hold their press conference is clear and unambiguous proof that they did not produce any noticeable amount of power through cold fusion." And, "We mortals cannot change those facts."

Dr. George Chapline of Livermore Laboratory said that the Utah results were "a case of self-deception...The claims of these people are preposterous on the face of it."

In his defense, Stanley Pons said, "We haven't any doubt that a deuterium fusion reaction is occurring in the palladium." And, "There is no reason the [fusion] reaction has to be the same [as in hot fusion]."

That, in a nutshell, is the source and content of the controversy. Now, briefly, let us look at how the press handled this controversy.

Jerry Bishop is the science writer for *The Wall Street Journal*. He has published some 30 reports on cold fusion during the past four years. In recognition of the quality of these reports, in January 1992 the American Institute of Physics gave him their Science-Writing Award in Physics and Astronomy. Aware of how different his reporting was from that of other publications, he offered the following admonition: "A reporter gets into a very dangerous situation when he begins to decide what the public should know or should not know."

The New York Times reported the controversy as a political story rather than a science story. The majority view set the tone or attitude for each story; the majority quickly became the "scientists," and the successful cold-fusion experimenters became the "enthusiasts."

The *Times* overlooked a third party in this contention: Mother Nature. In all this dispute, we must never forget that Mother Nature is a silent partner. Mother Nature knows, even if *The New York Times* does not, whether cold fusion is happening in the cells. Mother Nature will determine the outcome, and will do so quite without regard to the persuasion of the majority.

This concept is important because provincial newspapers use wire services most of the time, services that, except for Reuters, tend to follow the lead of the *Times*. As an editorial in the *WSJ* put it, "There is an odd habit among presumably competitive journalists...of deciding that they will agree with each other on the meaning of major news stories." The major media definitely agree with the *Times* on the meaning of the cold-fusion story: There is nothing there except unmitigated scientific hype.

A number of refereed scientific journals, such as *Fusion Technology*, *The Journal of Fusion Energy*, *The Journal of Electroanalytical Chemistry* and several others are willing to run the gauntlet of elite opprobrium and publish cold fusion technical articles.

The opposition to such articles, however, has not reached the point that it did during the anti-nuclear power days, when opposition to publication of particular articles, such as the Inhaber Report, was overtly organized and orchestrated.

The preeminent scientific journals—*Nature*, *Technology Review*, and *Scientific American*—that write for a broad audience are now closed to technical news and articles on cold fusion. But more significantly, they are also closed to discussions about the merits of studying the excess-energy phenomenon. From their point of view, there is no scientific controversy about the existence of cold fusion.

They do, however, comment editorially on the foibles of others. For example, at one of the early cold fusion wakes, the editor of *Nature* intoned, "Would a measure of unrestrained mockery, even a little unqualified vituperation, have speeded cold fusion's demise?" Or (for a second wake), I quote, "Farewell (not fond) to cold fusion...the cold fusion fuss is discreditable to the scientific community as a whole...so many serious people have been bamboozled for so long...a shabby example for the young...the time wasted...there is a limit to people's patience...." At no place in a full page of this censure is there any reference to the significance of the observed excess energy.

The editors of *Nature* have painted themselves into a tight corner with these words. I watch with anticipated amusement to see when the editors begin to have some first thoughts about digging themselves out. Scientists and science writers who address a broader audience than that offered by the refereed technical journals are thus led to periodicals on the publication fringe. To the dismay of these authors, articles derived from the Second Annual Cold Fusion Conference appeared, for example, in *21st Century Science and Technology*, a magazine published by the Lyndon LaRouche supporters.

Editors of the scientific press are often the ones to whom the general press looks for the meaning of science stories.

For example, the U.S. government's credibility in its 1992 charge that the Soviet Union was using a new T-2 mycotoxin-type of chemical weapon in Laos and in Afghanistan was effectively undermined by the appearance in *Scientific American* of a 10-page article purporting to show that "yellow rain," as it was called, was merely the excretions of honey bee swarms. A similar situation has arisen now with regard to the credibility of cold-fusion research results, but with a new twist.

As you may be aware, *Scientific American* is printed in many countries with more or less identical page content except for language. But in each country it is a separate publishing venture. The Nikkei publishing company publishes the Japanese version under the name *Saiensu* (Science).

In the March 1992 issue of the Japanese edition, the results of Takahashi's experiments and consequent theoretical musings were well reported in a story covering two pages and with what I will call quantized information—what others might call actual numbers. Naturally enough, some American scientists called

the offices of the American publication, whose longtime editor is Jonathan Piel, to ask why it had not published any cold-fusion experimental results in the United States.

His response is instructive. It was published in the (U.S.) 1992 May issue, which some of you may have seen. If one wants to understand what is going on—and that is a large part of my purpose—the answer, by editor John Horgan, is worth a brief analysis.

The editorial is entitled, "Japan, Cold Fusion and Lyndon LaRouche."

> If U.S. proponents of so-called cold fusion, otherwise known as fusion-in-a-bottle, are to be believed...cold fusion has been dismissed as "pathological science" by the vast majority of scientists since it was proposed three years ago by chemists B. Stanley Pons and Martin Fleischmann.

Notice how the editors put it. It is "proponents" versus "scientists."

> But the undeniably attractive idea of limitless energy from battery-like [sic] cells still has its believers.

Notice how "proponents" have now become "believers"—maybe members of some kind of religious sect.

> To regain respectability—and, even more important, funding—proponents are raising the familiar specter of Japan.

Notice that, in the eyes of the editors of *Scientific American*, the cold-fusion scientists do not have even "respectability."

> On paper, the Japanese effort in cold fusion does sound impressive. It involves some 100 Japanese scientists from 40 academic and industrial institutions...these workers are expected to attend the Third International Conference on Cold Fusion in Nagoya in October...In addition, a Japanese company is reportedly sponsoring research by Pons and Fleischmann in a laboratory near Nice, France.

Notice that "the Japanese effort," as described, is not about scientific work underway, but is merely an administrative report.

> Like their American counterparts, Japanese cold fusion researchers periodically announce astonishing results.
>
> Akito Takahashi of Osaka University recently claimed...excess power from an apparatus similar to the one originally used by Pons and Fleischmann...Yet Takahashi's results remain unreproduced by other researchers and unpublished in a peer-reviewed journal.

Notice that when this was written it had only just happened. Twelve months later, *Scientific American*'s readership had not yet been informed that Takahashi's work had been published in the *International Journal of Applied Electromagnetics in Materials* [3 (1993) 221] in 1992, nor had they been informed that his work had been reproduced by Dr. Edmund K. Storms at the Los Alamos National Laboratory, and published in *Fusion Technology* [23 (1993) 230] in 1993, even though editor Horgan admitted that Takahashi's claim represented "astonishing results."

> Fleischmann, when pressed, reluctantly confirms that he and Pons are indeed supported by Technova. Although he declines to reveal details about his work...

Notice that the editor avoids revealing to the readership that Pons and Fleischmann have published extended papers on their work in peer-reviewed journals.

> Although [Fleischmann] declines to reveal details about his work, he does note that "good information" on cold fusion can be found in *21st Century Science & Technology*, a journal published by followers of Lyndon H. LaRouche. LaRouche, who is now...serving a 15-year sentence for fraud, has previously claimed the existence of an international drug cartel run by the Queen of England.

I have to admit that the editors have there a nice punchline.

We are now being asked by the editors of *Scientific American* to associate the founders of what has become the scientific field of cold-fusion research with the works and claims of Lyndon LaRouche. This reminds me of a despicable practice once called guilt by association and now sometimes referred to as McCarthyism.

I ask you, is this sort of thing enough to explain why Stanley Pons departed his job and home in Utah and took his family to southern France to renew his work with Marvin Fleischmann?

Finally, on the editorial, note that it never mentions why it was written, what its sister publication in Japan is publishing, or that it was asked by American scientists for an explanation. For all their subscribers all context is omitted. I fear that that great publication is resting on its laurels.

The critics chose to trust only the nuclear physics of 50 years ago. They pointedly ignored the law of energy conservation, a much older and more fundamental regimen. So what? There's nothing particularly wrong with being wrong, except being wrong. On such a matter as this, they will find themselves in excellent company, and a lot of it. But how are we to explain the largess of vitriol that has and is being slung at Stanley Pons and Martin Fleischmann?

In this protracted conflict between theory and experiment always remember what it is that makes science *science:* Experiment prevails over theory. Theory never bows to experiment.

The excess energy of the Pons and Fleischmann cell has been competently demonstrated. Finding its source is a wholly legitimate scientific enterprise now well underway. *Nature* and *Scientific American* magazines have greatly hindered this scientific work by heaping calumny on those scientists engaged in identifying its source.

As happens in many new scientific developments that promise useful applications, this line of research is now dividing into two avenues. Systems for the generation of high levels of excess energy will largely disappear into the commercial laboratory, and there will be shrouded in the conventional secrecy of new-product development.

The scientific search for the origins of excess energy, and possibly immortal renown, will continue unabated in foreign laboratories. We must allow this exploration for the indefinite future as mother nature guards her secrets with great jealousy.

Whether this country will participate more than just peripherally depends en-

tirely on the character of our scientists in facing the politically inspired imposition of the press. Their track record to date is not encouraging.

I have brought you what, in our country, is a sorry tale of process, but, globally, is an exciting tale of progress. Between now and the turn of the century we should see a fascinating development of this new energy source.

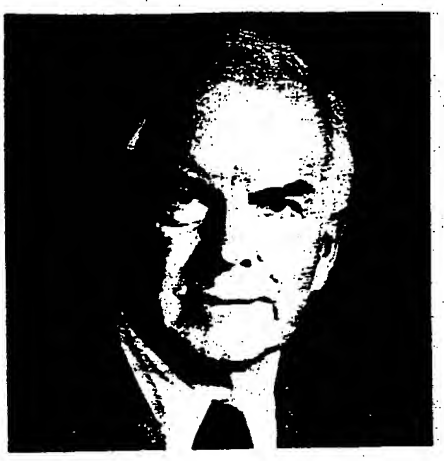
This paper was presented to the Western Maine Torch Club on September 30, 1992.

Biography

Charles Beaudette received his degree in electrical engineering from the Massachusetts Institute of Technology. After a two-year term of duty with the U.S. Air Force, Beaudette started his own company that manufactured an item of digital instrumentation. He later joined EG&G Corp. as an engineering manager working on facsimile transmission. Beaudette holds two patents on image compression, a technique used in facsimile transmission.

Beaudette moved to Maine in 1973 and worked as a consulting engineer and market analyst until 1987. Since then, he has devoted his time to writing on political and technical issues, and he has taken a particular interest in yellow rain and, more recently, cold fusion.

Beaudette lives in Cumberland, Me., with his wife and teenage son. He serves as a trustee of North Yarmouth Academy in Yarmouth, Me., and the World Affairs Council of Maine. His hobbies include history, politics, vegetable gardening, and the taming of feral computers.



Beaudette

1994 Paxton Lectureship Award

The Paxton Award, created in honor and remembrance of W. Norris Paxton, past president of the International Association of Torch Clubs and editor emeritus of *The Torch* magazine, is given to the author of an outstanding paper presented by a Torch member at a Torch club meeting during the 1993 calendar year. The winning author will receive an appropriate plaque, $100, and paid registration fees at the 1994 annual IATC convention in Norfolk, Va. The Paxton Award winner will be introduced at the 1994 convention banquet where he or she (or a designated representative) delivers the paper, on June 27, 1994.

Eligibility

The author must be a member of a Torch club and the paper must have been delivered at a Torch club meeting or a regional meeting between January 1, 1993 and December 31, 1993. (Note: Current officers and directors of the IATC are ineligible for this award during their terms of office.)

Procedure

Entries are to be typed and double- or triple-spaced. Include a cover sheet with the author's name, address, daytime telephone number and the date and place of the presentation of the paper. All identification, including identifying references within the paper, will be masked wherever possible prior to submission to the panel of judges. Entries may be submitted at any time but the deadline for receipt is March 1, 1994. Send to Paxton Award, International Association of Torch Clubs, Inc., 435 N. Michigan Ave., Suite 1717, Chicago, IL 60611-4067.

Judging

The reading and judging panel is composed of five people: a member of the Editorial Advisory Committee, a member of the board of directors of the IATC, one of the last five winners of the Paxton Lecture Award, and two Torch club members selected by the IATC board of directors. Judging is based on the principles set forth in the IATC brochure "The Torch Paper."

The winner of the Paxton Lectureship Award and the authors of all other entries will be notified no later than May 1, 1994.

Additional Information

There is no limit to the number of papers submitted by any one Torch club for this award.

A paper may be submitted by the author, by a Torch club colleague or by an officer of the Torch club. It is preferred that, however the paper is submitted, it receive the endorsement of the club as a Paxton Lecture Award submission through its officers, secretary, or the executive or program committee.

The winning paper is to be presented at the 1994 annual convention by the author or an author-designated representative from the author's local Torch club.

The Paxton Lecture Award paper will be published in the Fall 1994 issue of *The Torch* magazine. Other entries will be forwarded to the Editorial Advisory Committee for review for possible publication in the magazine.

The publishing fiasco of the century

BY EUGENE F. MALLOVE

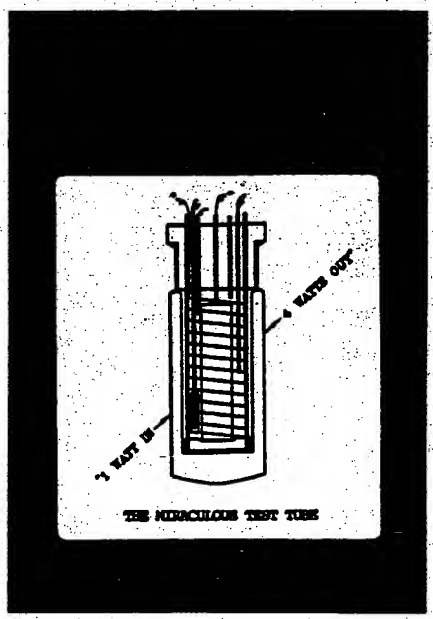
Cold Fusion: Scientific Fiasco of the Century

University of Rochester Press, 1992, 259 pages, $45
by Professor John R. Huizenga
Co-chairman, U.S. Department of Energy Cold Fusion Panel, 1989.

What can one say about an author who ignores essentially all the positive evidence for cold fusion, who leaves out virtually *everything* after 1989, who says *nothing* about the revolutionary yet ultra-cautious cold fusion work carried out by the conservative Electric Power Research Institute, who *denies* that a major cold fusion effort is under way in Japan, who doesn't even mention the cold fusion experiment controversy at MIT and the controversy about the Caltech "negative" cold fusion experiment? Not much. That is, unless you know that John Huizenga was the first Department of Energy-designated general in its unconscionable war against cold fusion.

In 1992, as the pace of the cold fusion revolution quickened in Japan and in numerous "underground" laboratories in the U.S., France, Italy, and elsewhere, John Huizenga finally got his cold fusion book. Since 1989, attacking cold fusion research and scientists curious about the strange phenomenon has been Mr. Huizenga's pastime—one might say, his obsession. And well it might be, because his reputation is at stake. Huizenga says that interest in cold fusion is "dying," but it is *he* who is going down for the last time.

As the co-chairman of the Department of Energy's Energy Research and Advisory Board (ERAB) Cold Fusion Panel for the mere six-months in 1989 that it officially investigated cold fusion, John Huizenga and his fellow panelists were given an awesome civic responsibility. Their duty: to assess the numerous shocking, sometimes apparently conflicting, and always intriguing reports of what had come to be called "cold fusion"—provocative evidence of significant excess power production in palladium-platinum electrochemical cells filled



with heavy water, as well as nuclear products from possible heretofore unknown nuclear processes.

Drs. Martin Fleischmann and Stanley Pons made the original bold claims in Utah at a press conference on March 23, 1989, which has since been severely criticized by skeptics and even so-called "believers."

However, the method used to disclose this shocking finding and the intriguing political-scientific-media interplay before and after is not the main issue. Of overriding importance was and is:

Is cold fusion real, and, if so, what to do about it?

Yes, in retrospect, the premature announcement was a disaster, which Pons and Fleischmann themselves had resisted; they wanted to work another year and a half before reporting their results. And when they did announce, their hands were tied by patent lawyers who prevented adequate disclosure. The politics, the intrigue, the ongoing fight over patent rights are not pretty, and they are real. Nobody denies that. But these have nothing whatsoever to do with the basic science of cold fusion. The news conference and the problematic press release are not the issue. The DOE did not ask Huizenga to judge the aesthetics or the propriety of people's behavior, it asked him to look at the scientific facts—and clearly he didn't.

Disagreement has its limits

In March, 1989, if the cold fusion report was not just a big mistake, it was possible that a new kind of nuclear process had been discovered—possibly a new form of metal atomic lattice-induced fusion, or possibly new kinds of chemical reactions, but in any case a chance of something new to science. Most people thought this was wonderful. At least there would be an exciting new detective story in science, but Huizenga and his ilk thought it was terrible. If the claim of excess power generation were true and this heat were accompanied mainly by relatively low-levels of neutrons and tritium, cold fusion would, indeed, be a revolutionary discovery with far-reaching implications for the world energy economy.

If the new power source could be reduced to practical technology, the planet would have an infinite source of energy from sea water in the hydrogen isotope, deuterium. Many working in the cold fusion field, including myself, after being quite skeptical for many months or years, are now convinced that "cold fusion" phenomena are real, and that the revolution will come. It will only be a matter of time.

Of course, there are those who disagree with this assessment, and this is how it should be in science. Still disagreement has its limits.

In 1989, instead of adopting a completely open-minded view of startling new data and getting to the bottom of what was going on, the scientific process was derailed.

Disaster struck: in walked Professor John Huizenga. Under the strong influence of Huizenga and his preconceived belief that cold fusion "contradicted the foundation of nuclear science" (p.viii), the Department of Energy cold fusion panel engineered a highly flawed, indefensible document. Its negative conclusions were largely solidified (by Huizenga's own admission) by July, 1989, barely three months after the panel began its work.

By the end of October, 1989, the group's work was reduced to a final report with conclusions that have, if not entirely stymied, seriously hampered the scientific investigation and commercial development of cold fusion power in the United States.

But from Huizenga's book, which recounts the "investigation" by the ERAB panel, there may yet come *some* good, because *Fiasco* proves beyond question that at no time in the panel's deliberations were serious thoughts given to even the *possibility* that a new form of nuclear process might be occurring in metal lattices.

It is proof positive that the study was biased from the outset and easily could be construed as a major deception perpetrated on the people of the United States. Each of the panelists bears some responsibility in this regard, but none as much as Huizenga, who was clearly the driving force in the rush to judgment. Some of the less-involved panelists upon investigating for themselves what has really been going on in cold fusion research since they signed the ERAB report, might have second thoughts about their approval.

From this influential document has come a poisoned scientific atmosphere, media ridicule of continuing honest scientific investigations, a cut-off of DOE funding for cold fusion, the banning of even "bootlegged" cold fusion research at some federal laboratories—in other words, at the very least, an embargo against a new scientific field.

The continuing news of successful and provocative cold fusion research in Japan, the funding for cold fusion from the private Electric Power Research Institute (EPRI) in the U.S., and multi-million dollar funding by the Japanese Ministry of International Trade and Industry (MITI) must grate on Huizenga. His two favored villains, Pons and Fleischmann, hard at work at a laboratory in France funded by Japanese businesses affiliated with Toyota, have achieved reproducible boiling in cold fusion cells, which has vaporized all the heavy water electrolyte—over and over again.

But Huizenga says 'nay'

Such spectacular results have become the order of the day in the cold fusion field. But Dr. Huizenga doesn't believe *any* of the cold fusion evidence. He says that every bit of it can be characterized in two words—"pathological science." All these hundreds of scientists in over a dozen countries still working or interested in cold fusion are deluded.

Professor John Huizenga

John Huizenga attended the Third International Conference on Cold Fusion (ICCF3) in Nagoya, Japan (Octobe 1992) and ICCF4 on Maui, in December 1993. At no conference session did he offer any public technical comment, nor did he present any paper. However, after both cold fusion conferences the U.S. press dutifully printed Huizenga's remarks to reporters that he still considered cold fusion to be "pathological science" and that no further evidence had emerged to change his mind. Clearly, Huizenga is still at war with cold fusion. Why?

Excess heat in cold fusion experiments is illusory, says Huizenga, even though he cannot point to any errors being made. Tritium generation found by over 40 cold fusion groups is a vast mistake, and in one famous case, possibly fraud, says Huizenga. In his book he continues to give credence to Gary Taubes' sophomoric charge of tritium-spiking of cold fusion cells at Texas A&M University. Texas A&M looked into these charges long ago and showed they were without foundation. Furthermore, others have shown that it is not even physically possible to "spike" with tritiated water to get the results of that research group.

Neutron bursts and continuous neutron emissions encountered by numerous laboratories around the world are all erroneous. The ones Huizenga thinks he can't outright dismiss he says are likely to be wrong or unimportant if they are right. Charged particle emissions and several helium findings are all wrong, says Huizenga. Cold fusion research is a gigantic waste of time and money, says Huizenga. "The world's scientific institutions have probably now squandered between $50 and $100 million on an idea that was absurd to begin with," (p.184) says Huizenga.

Over and over again, Huizenga employs the pathological science label and inference. That is precisely why this book may come to be known as the "publishing fiasco of the century," perhaps in a class with Rene Blondlot's famous tome on non-existent "N-rays" earlier this century. Long after "N-rays" were convincingly disproved in a decisive experiment, their inventor, Blondlot, carried on with his obsession. Similarly, we ask: Has Huizenga fallen into the same kind of trap? Will Huizenga find it virtually impossible to accept cold fusion, to admit that he was wrong—even when commercial power devices pass juice into his wires?

Don't expect to learn about the other side, the latest positive cold fusion experiments, in Huizenga's book. In fact, there isn't even appropriate discussion of some very good cold fusion experiments that were done long ago—at the time Huizenga was masterminding his DOE report. And definitely don't expect to find what most "believers" really *believe*. He does not adequately discuss their theories. He cites preliminary 1989 versions of theories that have since gone through many iterations and have been expanded and improved. He cites theories, such as the valiant Walling-Simons theory, that were abandoned in 1989 in favor of better ideas.

In fact, virtually every time the word *theory* appears in *Fiasco* it is set off in sarcastic quotes—as in "theory." It is as though no one should even attempt to explain what to Huizenga from the outset was so obviously impossible nonsense.

Huizenga maligns the evidence and wantonly dismisses all theories *a priori*. He says of theorists: "Conventional nuclear physics was

declared invalid in metallic lattices by fiat." No cold fusion theorist ever made any such assertion. Here is what most cold fusion believers *do* believe has been established: The excess energy—beyond the electrical power put into an electrochemical cold fusion cell—is in many cases so large (tens to hundreds of megajoules per mole of palladium atoms accumulated over long and sometimes short periods of time) that this heat cannot be due to ordinary chemistry.

Chemistry or other conventional energy storage mechanisms cannot explain these excess energies, period! So the energy could be due to nuclear reactions, mini-black holes, interactions with cosmological dark matter, or microscopic broccoli plants, but *it must be explained* and conventional chemistry doesn't hack it.

Most cold fusion "believers" are very conventional and are thus more attracted to nuclear explanations than to mini-black holes. They have noted that in the same or similar electrochemical systems, nuclear products—tritium, neutrons, helium—have been convincingly detected. It matters not a jot that these particular already detected particles are not fully commensurate with the demonstrated power levels (as Huizenga demands *ad nauseam*). Cold fusion investigators have been saying all along that the particular main-line reaction path could be isotopic shifts from the transfer of neutrons (from deuterium, for example) to other elements—the palladium, the lithium, the light hydrogen, or even other impurities known to be in the complex metal system. These are not easy to unravel, particularly because reproducibility of cold fusion reactions has been a serious problem, exacerbated by the zero DOE funding situation that Huizenga and Company have left us.

In most cases so far, these reaction products would not have been readily seen because of their low levels or because resources were not available to hunt for them. That these products have not been neatly packaged for him, and the mechanism explained from day one, proves to Huizenga that cold fusion is without substance. This appears to be a deliberately misleading contention and a faulty approach to science. *Fiasco* is, quite literally, a bizarre pastiche of misinformation.

"Surprises do occasionally occur in science." (p. viii)

—John R. Huizenga, Tracy H. Harris Professor of Chemistry and Physics

Huizenga's opinion of cold fusion at the outset of the controversy is documented compendiously in *Fiasco*. When the Congressional inquiry into this matter is eventually held, the evidence of his words will be more than adequate to prove that he was hopelessly biased from the start. Why was such a skewed chairman chosen?

Is that you, Darth Vader?

If you know Washington and the federal research establishment, you already know the answer: Huizenga was chosen to be the hatchet man. The DOE wanted to strangle the cold fusion "nonsense" in its cradle, before it became too noisy an embarrassment to DOE's expensive and troubled $500

"A foolish consistency is the hobgoblin of little minds..."

—Ralph Waldo Emerson, 1841

million a year *hot* fusion program. In describing his appointment to head the ERAB panel, Huizenga says, "My initial feeling was that the whole cold fusion episode would be short-lived and that it would be wise to delay appointing such a panel." (p.42) Yet Huizenga asserts, "In my close association with each of the panel members, I saw no evidence of bias on the part of any panel member." (p.104) He forgot to examine his own soul.

Huizenga claims that those who thought they had found no evidence of cold fusion were ". . . reluctant to publicize their findings. Firstly, these groups were cautious, wanting to be sure that they themselves had not made mistakes."

Not so! I was the chief science writer in the News Office at MIT at the time and I can testify that the MIT Plasma Fusion Center-Chemistry Department group investigating cold fusion salivated at the prospect of destroying Pons and Fleischmann, almost from the first day. Director of the Plasma Fusion Center, Professor Ronald R. Parker, and Professor Ronald Ballinger in late April, 1989, helped launch a vicious attack on Pons and Fleischmann with a deliberately planted story in *The Boston Herald*. The taped interview with the Herald Reporter is now public record.

So many other things are mysteriously missing from *Fiasco*. Although the group is mentioned by name, we read nothing of the pioneering work of Dr. Michael McKubre and his EPRI-funded group at SRI International in Menlo Park, California. This team is widely acknowledged by both believers and even fence-straddlers to have done some of the most careful cold fusion calorimetry in the world. Although a tragic and still puzzling explosion in a SRI cold fusion experiment killed electrochemist Andrew Riley on January 2, 1992 (also not mentioned by Huizenga), EPRI is still solidly behind the McKubre work. Why *doesn't* Huizenga discuss McKubre's work? Readers would very much like to know what errors he was able to find in it.

He devotes only one paragraph to the Second Annual Conference on Cold Fusion in Como, Italy, held in July, 1991. He says nothing about the new findings that were presented there, which were numerous and impressive.

In fact, world-class electrochemist Dr. Heinz Gerischer of the Max Planck Institute attended the conference as a skeptic, but left convinced that nuclear reactions at some level were, indeed, occurring in metal lattices. Later he wrote in a memo to the German government: "The fact that in the Republic of Germany this work has been inhibited is no longer justified. It could, later on, be regarded as a very unfortunate gap in German research when compared with the present activity in other countries and particularly in Japan."

However, Huizenga managed to find space in his brief paragraph on Como to explain why Steven Jones, a proponent of low-level cold fusion neutrons who does not believe that the excess heat is of nuclear origin, declined to attend the conference.

Huizenga distorts the truth in many ways. The final report of the Utah National Cold Fusion Institute (1991) was available to him and contains clear descriptions of *reproducible* tritium generation in experiments by the ultra-cautious electrochemist Dr. Fritz Will. Yet Huizenga asserts, "There has been no sign of this growth of understanding of cold fusion either in the production of fusion products or excess heat." (p.126) He makes the same assertion at greater length on page 102.

Describing the conclusions of his panel's report, he points proudly to its objective to cut off funding: ". . . there should be no special funding for cold fusion. This recommendation was meant to insure [sic] that no research centers or special programs to investigate so-called cold fusion phenomena would be developed with federal funds."(p.101) Huizenga obviously fancies himself a hero upholding the purity of science.

And it was not only funding that he sought to halt. For example, he unabashedly admits his role in trying to prevent *Wall Street Journal* senior science writer Jerry Bishop from receiving the American Institute of Physics award for science writing for his series of cold fusion stories. Even some skeptics, slightly less ardent than Huizenga, have appreciated and praised Bishop.

Huizenga bemoans the publication of theories of cold fusion. He wants to keep the technical literature safe from pernicious ideas, that is, ones he can't compass.

Fiasco does, however, have several high points for which we should thank the author. I was also delighted to see confirmed the facts which I disclosed in *Fire from Ice* about the attempted resignation from Huizenga's panel by physics Nobel laureate Norman F. Ramsey. It was the last session of the panel's meeting and the less involved co-chairman Ramsey, though not convinced that cold fusion effects were real, was uncomfortable with the report's thoroughly negative tone, given the uncertainties that remained. In exchange for not resigning, which would have been a major PR snafu for Huizenga's panel, Ramsey was apparently able to extract from an unwilling Huizenga the addition of a qualifying preamble. This "weakened the report somewhat," according to Huizenga. (p.92) Huizenga says he was perturbed that this (to others) eminently reasonable preamble was "noncommittal and evasive." Just as I wrote in my book, "He [Huizenga] wanted the final knife to go in with a totally negative report." Among other things, the preamble states clearly: *"Consequently, with the many contradictory existing claims it is not possible at this time to state categorically that all the claims for cold fusion have been convincingly proved or disproved."* In my view, Ramsey was a hero for having won that much from Huizenga, but it would have been far better had he resigned from the panel.

Huizenga's book is a masterpiece in reasoned irrationality—a seeming contradiction in terms, but very apt for this exotic work. Professor Huizenga's words reveal him to be an incompetent, who even with his presumably broad and detailed knowledge of nuclear physics, has not assimilated the most elementary understanding of science. He does not recognize it as a process of discovery whose lifeblood is anomaly, the new, the different. How else can science progress? Huizenga's view of science is stodgy, status quo, stultified, and steeped in mind-boggling conventionality.

Read it and weep

With all this said, "Fiasco" deserves to be read, but not bought. It is an object lesson in the hazards of labeling honest science "pathological." Perhaps we should rejoice in "Fiasco," because here we have, once and for all, the perfect demonstration of how science should not be done when confronted with puzzling results:

1. Start with the preconceived idea that reported data suggest a phenomenon that is impossible; 2. Use a standard theory to prove impossibility (much as Simon Newcomb "proved" that heavier than air flight was impossible a few years before it was accomplished by the Wright brothers); 3. Continue for years to reject *every* experiment with positive results as "obviously in error," while accepting supposedly "negative" experiments done in a few months or weeks time by "first-tier" universities and labs; 4. Ignore and mock all theories that attempt to explain the phenomenon—even those that employ accepted mathematical formulations of quantum mechanics. (And, for good measure, ignore later published versions of initial theories that are available in the open literature.); 5. Command a clique of like-minded scientific doubters on a federal panel and foist a deceptive rush-to-judgment onto an unsuspecting public, ill-equipped to second-guess "official" scientific wisdom.

This is a lesson we could well have done without. It would have been so much better had Huizenga been scientifically up to his civic responsibility on the cold fusion panel. Huizenga is at least partially right in one of his ideas (though not in the anti-cold fusion sense that he intended), as expressed in part of the last sentence in his book: "...the scientific process works by exposing and correcting its own errors." A bitter irony here: the data from cold fusion experiments weren't "preposterous," Huizenga was. He will be corrected.

recommends against the establishment of special programs or research centers to develop cold fusion. However, there remain some unresolved issues which may have *interesting implications.* [author's italics] The Panel is, therefore, sympathetic toward modest support for carefully focused and cooperative experiments within the present funding system." Overall, a skeptical assessment, written from the perspective that all that had to be done to put the final nail into the coffin of cold fusion was to go after the slightly worrisome lingering doubts. No sense of urgency is communicated for finding out whether there might really be a new phenomenon. The "interesting implications" alluded to are never clearly spelled out. The phrase was vague, as intended, and as we are seeing more and more, the implications were, indeed, "interesting"!

To the ERAB Panel's credit, in the report's more detailed "Conclusions and Recommendations" section, there are several good and pointed recommendations. Among the suggestions: ". . . research efforts in the area of heat production focused primarily on confirming or disproving reports of excess heat"; ". . . investigations designed to check the reported observations of excess tritium in electrolytic cells . . ."; and "If the excess heat is to be attributed to fusion, such a claim should be supported by measurements of fusion products at commensurate levels."

But this seems, in retrospect, like so much window dressing to the Panel's real conclusion, namely that nothing particularly interesting, certainly nothing of a practical nature, could come out of this work. The Panel's purpose, it seems, was to give not the slightest bone of encouragement to the voices in the wilderness that were claiming the opposite.

Some perceptive souls in the media saw the Panel's report as a smoke screen. Editor Elizabeth Sullivan of the Cleveland *Plain Dealer* newspaper, being aware of the provocative work being done in her own backyard at Case Western Reserve University, ended her editorial assault on the DOE panel's conclusions with: "What prudes scientists have become if they *fail* to be intrigued by the unexplained. And how unlikely to find the answer if they fail to look."

✳ A Flawed Report

The central problem of the Panel, one that all along characterized most of the skeptics' efforts to come to grips with cold fusion, was a stubborn insistence that it was unlikely that any new physical mechanism was at work. They insisted that all mysteries had to be seen in this light, hence the incessant invoking of other supposed physical "requirements" that the new phenomenon should obey. Very rarely in the ERAB report was

there even a bow to a possible new physical paradigm, and when there was, the pleasantry was quickly withdrawn with a negative remark.

The executive summary could state, with neither embarrassment nor qualification, in referring to the Jones and others and Frascati work, "Neutrons near background levels have been reported in some D_2O electrolysis and pressurized D_2 gas experiments, but at levels 10^{12} below the amounts *required to explain the experiments claiming excess heat.*" [author's italics] Implying, of course, that cold fusion would have to work by the same mechanism as known hot fusion reactions. The summary goes on to state, "Although these experiments have no apparent application to the production of useful energy, they would be of scientific interest, if confirmed." It was an echo of the earlier editorial in *Nature.* Only of "scientific interest"? It would have been far more appropriate to say "*dramatic* or *extraordinary* scientific interest," given that subtle and unexpected phenomena have a long history of becoming very useful in technology. Did anyone remember that hot fusion had pulled off a minor miracle of its own in the last two decades, climbing 10,000-fold in performance? Where was scientific imagination and creativity here?

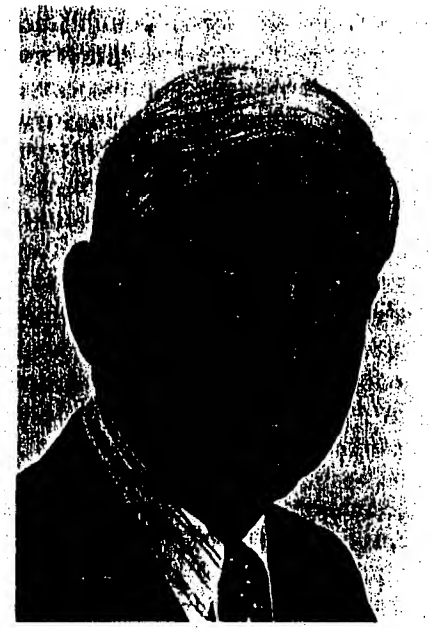
The irony of the report was its contention that there might be some "scientific interest" in a possible new phenomenon and that reports of anomalous heat were "not persuasive"—by implication, not entirely ruled out. On the other hand, it was entirely too fond of the refrain—made several times in various forms—"no apparent application to the production of useful energy."

The report's saving grace was several assertions made in the "Preamble" to its conclusions and recommendations. However, the softening language was inserted only on the last day the Panel met, to satisfy the strong complaint of physicist Norman F. Ramsey of Harvard University, who weeks earlier had won the 1989 Nobel Prize for physics.

Attendees reported that Ramsey was so dissatisfied with the Panel's work and blanket negative conclusions (written largely by cochairman Huizenga), which earlier had been unanimously agreed on by other Panel members, that he told Huizenga that he wanted to resign if the conclusions were not modified. Huizenga was extremely angry and upset, but very reluctantly relented and allowed Ramsey to write a few sentences of softening, qualifying language that appeared in the report's preamble. This was an open public meeting with press in attendance, yet the media did not report that Ramsey had made an actual resignation threat, only that he had been dissatisfied with some of the draft report's language. Ramsey's resignation would have dealt a severe blow to the Panel's work.

Unfortunately, Ramsey had only been able to attend the first and last meetings of the Panel, and it is hard to know whether he would have been more or less negative about the report had he been present

One of the staunchest critics of cold fusion research, Dr. John R. Huizenga, Professor of Chemistry and Physics at the University of Rochester. (Courtesy University of Rochester)



Dr. Norman F. Ramsey, Professor of Physics at Harvard University and winner of the 1989 Nobel Prize for Physics, cochaired the DOE Cold Fusion Panel with Dr. John R. Huizenga. (Courtesy Harvard University)

in the middle phase. The adjusted language mollified Ramsey enough to allow him to stay on. The preamble left open the distant possibility that cold fusion might be real after all. In part it read: ". . . it is difficult convincingly to resolve all cold fusion claims since, for example, any good experiment that fails to find cold fusion can be discounted as merely not working for unknown reasons. Likewise the failure of a theory to account for cold fusion can be discounted on the grounds that the correct explanation and theory has not been provided. Consequently, with the many contradictory existing claims it is not possible at this time to state categorically that all the claims for cold fusion have been either convincingly either proved or disproved."

Cochairman John Huizenga was not happy with this "weakening" of the report, the first draft of which he was the primary author. He wanted the final knife to go in with a totally negative report. There is

ative conclusions, if Ramsey had carried through with his threat. Federal cold fusion funding hung by that thin a thread.

Spoiling the otherwise meritorious sentiment, inserted at the 11th hour to please Ramsey, was a fifth conclusion: "Nuclear fusion at room temperature, of the type discussed in this report, would be contrary to all understanding gained of nuclear reactions in the last half century; it would require the invention of an entirely new nuclear process."

Of course! That was exactly the point that cold fusion proponents had been making all along. This conclusion was most certainly *not* being put forth as a compliment to those who were working on theories to explain cold fusion. Its intent was to reiterate the cry of the skeptics against a new scientific paradigm; the experimental evidence seemed to them overwhelmingly on their side.

Immediately preceding this conclusion is further evidence that the Panel was assuming that cold fusion had to be understood from straight extensions of known mechanisms—as though all the phenomena of nature had to be codified according to previous schema. The example of superconductivity alone should have warned them against that mistake. Nevertheless, with a faulty "appeal to authority," the Panel's fourth conclusion stated in part: "Current understanding of the very extensive literature of experimental and theoretical results for hydrogen in solids gives no support for the occurrence of cold fusion in solids. . . . The known behavior of deuterium in solids does not give any support for the supposition that the fusion probability is enhanced by the presence of the palladium, titanium, or other elements." Perilously close to saying "all that can be known about the palladium-hydrogen system is already known."

It gets worse. On page six of the ERAB report is the statement, "A third reason for skepticism is that cold fusion should not be possible based on established theory." Then follows a page of discussion that presents the well-known physical foundation of hot fusion, plus a justification for ruling out cold fusion based on little more than that the conditions hot fusion or muon-catalyzed fusion require can't possibly be present in the recent cold fusion experiments. Ergo, it is unlikely that cold fusion can be real.

✳ A Not-So-Secret Meeting

If cold fusion had "died" with the ERAB report cooked up in July and ratified in November, it was reborn in October, during a calm before a storm. A hush-hush meeting of 50 scientists came together (October 16–

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Reproducible tritium generation in electrochemical cells employing palladium cathodes with high deuterium loading

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Abstract

Reproducible tritium generation well above background has been observed in tightly closed D_2SO_4-containing cells in four out of four Pd wire cathodes of one type. Tritium analysis was performed before and after each experiment on the Pd, the electrolyte and the gas in the head space. No tritium generation was observed in four identical Pd cathodes in H_2SO_4 cells operated at the same time under the same conditions. A cyclic loading–unloading regime with low current densities, rather than the usual continuous constant current regime, was employed to attain D/Pd and H/Pd loadings of 1 ± 0.05 reproducibly. D/Pd loadings greater than 0.8 ± 0.05 appear to be necessary to generate tritium. The largest amount of tritium, generated in 7 days of continuous electrolysis, was 2.1×10^{11} tritium atoms, compared with a background of 4×10^9 tritium atoms. The concentration of tritium and its axial distribution in the Pd were determined and concentrations of up to 9×10^{10} atoms/g Pd were found compared with a maximum background of 5×10^8 atoms g^{-1}. The T/D ratio in the Pd is about 100 times larger than in the electrolyte or gas and indicates that tritium generation occurs in the Pd interior rather than at its surface. No tritium generation was observed in two other types of Pd electrodes in D_2SO_4, despite the attainment of D/Pd ratios near 1 : 1. Thus high D/Pd ratios appear to be a necessary but not sufficient condition for tritium generation in D_2SO_4 electrolysis.

INTRODUCTION

Since Fleischmann, Pons and Hawkins [1] published their original paper on "electrochemically induced nuclear fusion of deuterium" at ambient temperature

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and Jones et al. [2] reported on their "observations of cold nuclear fusi... condensed matter", many groups have reported the occurrence of nuclear ... tions in deuterium-loaded metals. In particular, a large number of groups ... reported evidence for neutrons [3–10] and tritium [11–25]. While neutrons ... generally been detected at only very low levels, tritium generation has ... reported at levels 10^7–10^9 times higher. Unfortunately, these findings ar... generally reproducible or predictable, which has made systematic investigation... these phenomena most difficult. Furthermore, doubts have been voiced [26,2... to whether tritium found in Pd cathodes, employed in heavy water electrolysis... been generated by "cold fusion" reactions or whether it was present in... palladium as a contaminant before any experiments were conducted. Such do... have not been confirmed in a study of the behavior of deliberately tritium-de... Pd [28] and in recent analyses of large numbers of as-manufactured Pd sam... using two different methods [29,30].

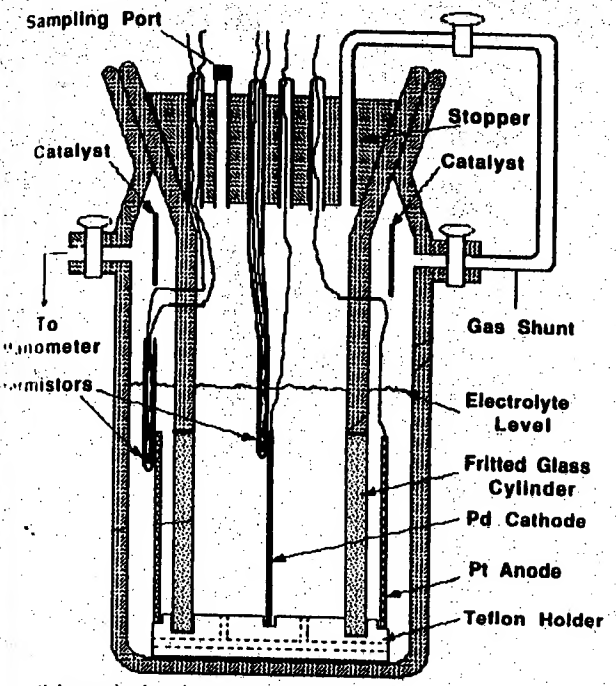
The present study reports on the reproducible generation of tritium at l... well above background in Pd cathodes during heavy water electrolysis. Re... ducibility of tritium generation has been achieved by developing a method fo... reproducible achievement of D/Pd loading ratios near unity. A closed-cell de... with internal gas recombination was employed, and the tritium contents of... electrolyte and the gas above the electrolyte were determined prior to and afte... experiment. Pieces of Pd wire adjacent to that used as the electrode were anal... before each experiment and the active electrode was analyzed after each exp... ment. A light water control cell was always run in electrical series with every ... cell under essentially identical conditions. This procedure always allows de... comparison of any tritium in the D_2O cell and the H_2O control cell.

EXPERIMENTAL

Cell design

In contrast with most cell designs used in cold fusion studies, the cell used... this study employed a fritted (porous) glass cylinder to separate the Pd cath... from the Pt anode compartment. A similar design has been used by a group at... Bhabha Atomic Research Centre, Bombay, India [31]. Such a design prev... direct contact of O_2 gas bubbles, formed at the anode, with the cathode ... reduces the rate of diffusion of dissolved O_2 to the cathode. The influence of... on the cathode through the gas head space is negligible owing to a gas recomb... tion catalyst and excess $D_2(H_2)$ in the head space. The cell is sealed sufficie... well to allow a vacuum ($< 10^{-3}$ Torr air) to be achieved using a mechanical pu... and has provisions to measure the D/Pd (H/Pd) loading ratio continuously.

Figure 1 shows a schematic drawing of the cell. The Pd electrode (1 or 2 ... diameter wire) is placed at the center of the fritted glass tube which in turn ... surrounded by a 0.1 mm thick Pt foil cylinder (anode) to provide uniform curr... distribution. The fritted glass tube has holes of mean diameter 200 μm. A Pd wi...



Schematic drawing of electrolytic cell.

...ged to the $\alpha+\beta$ phase mixture, is used as a reference electrode in most ...riments. The various parts are kept in position at the bottom of the cell with a ...on holder, which has channels to equalize the electrolyte levels in the two ...partments. The anodic and cathodic compartments are connected by an ...rior loop so that the gases can recombine on a Pt catalyst placed above the ...lyte. The electrolyte volume in the cell is approximately 38 cm^3, whereas the ...l gas volume is approximately 300 cm^3.

A simple water-filled manometer, comprising two burets which are connected at ...r lower ends with flexible tubing, serves to determine volume changes in the ... volume above the electrolyte which are proportional to the loading ratio. This ...nique, developed in the 1950s [32], was improved and successfully applied in ...nt D_2 loading studies of Pd [33]. The use of H_2O in the manometer results in ... transfer of a small amount of H_2O to the 0.5 M D_2SO_4 electrolyte. The rate of ...O transfer to the 0.5 M D_2SO_4 was determined experimentally as 2.8×10^{-3} ... per day, equivalent to a contamination of the D_2SO_4 by H_2O amounting to ...% per day.

...terials and reagents

To avoid problems of glass dissolution and plating of glass components on the ...l cathode, as encountered in LiOD solutions [13], our experiments were carried

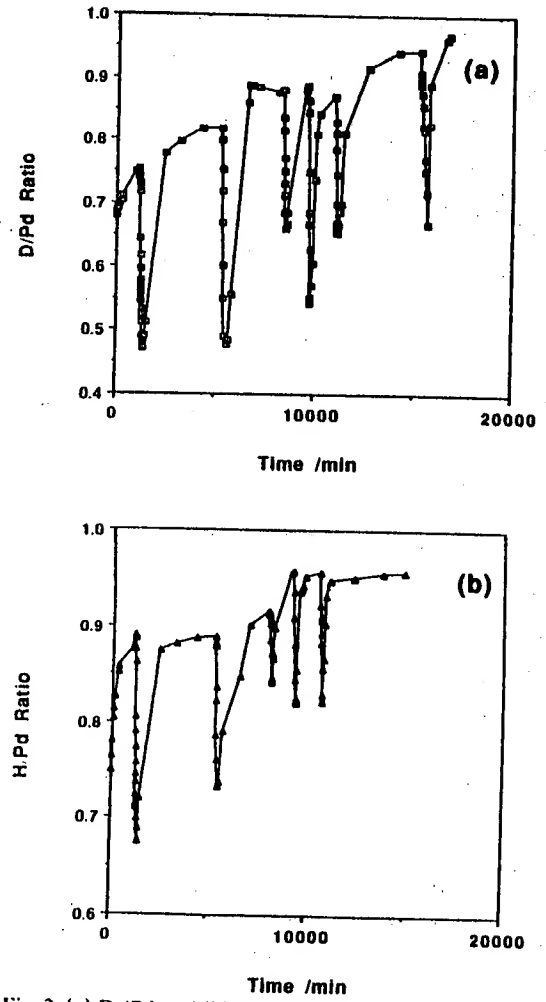


Fig. 2. (a) D/Pd and (b) H/Pd loading ratios as a function of time: 0–1109 min, 30/10 mA charge to 1377 min, 30/20/10 mA discharge (D); to 5253 min, 10 mA (C); to 5619 min, 30/10 mA (D); to min, 10 mA(C); to 8545 min, 30 mA (D); to 9588 min, 10 mA (C); to 9788 min, 30/20 mA (D); to min, 20 mA (C); to 11126 min, 30 mA (D); to 15266 min, 10 mA (C); to 15709 min, 30/10 mA (D) to 16737 min, 20/10 mA (C).

out in 0.5 M H_2SO_4 for the light water control cells and 0.5 M D_2SO_4 for the heavy water cells. The heavy water (99.9% isotopic purity) was purchased from Cambridge Isotopes Laboratories Ltd. The 0.5 M D_2SO_4 solution was made by diluting conc. D_2SO_4 (98%, balance mostly D_2O, Aldrich Chemical Co. Inc.) with D_2O; the 0.5 M H_2SO_4 solution was made by diluting conc. H_2SO_4 (96%, Baker Analyzed Reagent) with deionized H_2O. In one experiment, Li_2SO_4 (solid 99.9% Aldrich Chemical Co. Inc.) was added to the acids.

The H_2O and 0.5 M H_2SO_4 contained no measurable tritium within the accuracy of the liquid scintillation counting [29,30] i.e. 1 dpm ml^{-1} (decomposition per minute per milliliter) or 9.28×10^6 tritium atoms ml^{-1}. The D_2O and 0.5 M D_2SO_4 had typical tritium contents of 10 dpm ml^{-1}. Occasionally, however, batches with D_2O from the same supplier had tritium contents of up to 300 dpm ml^{-1}. These were rejected, with the exception of one experiment where the results of the analysis were completed only after the experiment had started.

Deuterium gas was purchased from Air Products & Chemicals Inc. and Alphagaz-Liquid Air Corporation. Both suppliers use heavy water electrolysis to produce D_2 gas, and both purchased the heavy water from the same source (Ontario Hydro, Canada). According to our analysis [34] the gas purchased from Alphagaz had a low tritium count of 110 dpm/l^{-1} of D_2 gas (0.05 nCi l^{-1}). The gas supplied by Air Products had a count of 0.13–0.14 nCi l^{-1}. Similar results were obtained by T.N. Claytor at Los Alamos National Laboratory.

Cathodes were of three different types or origins: (a) 1 mm diameter cold-drawn wire (99.99% purity) from Aesar-Johnson Matthey; (b) 2 mm diameter cold-drawn Pd wire (99.9% purity) from Hoover & Strong; (c) 2 mm wide × 0.5 mm thick cold-rolled Pd + 5% Li alloy ribbon prepared at the University of Utah [35]. The electrodes were approximately 3 cm long. Analysis for tritium contamination of pieces (later increased to more than 130 pieces) of as-supplied Pd [30] from Johnson Matthey and Hoover & Strong showed no tritium contamination within the accuracy of the analytical technique, i.e. 5×10^8 T atoms/g Pd or approximately 1 T atom/10^{13} Pd atoms.

Anodes were cylinders of 2.8 cm diameter and 3 cm length, made from 0.1 mm thick Pt foil (99.98% purity) from Johnson Matthey. The Pt was provided with a Pt black layer by plating from $PtCl_2$ solution employing well-known procedures.

A 1 cm wide × 8.5 cm long piece of fuel cell grade Pt catalyst on Ag-plated Ni screen (type ESN by E-TEK Inc.) was used as a recombinaton catalyst. It was positioned in the gas head space of the anode compartment approximately 3 cm above the electrolyte level.

Experimental set-up

All experiments were performed using an identical light water control cell run in electrical series to the heavy water cell. The two cells were contained in two separate water baths of type EX-510D (NESLAB Institute Inc.) which controlled the temperature at 27 ± 0.02°C. The laboratory was air-conditioned, with room temperature in the first week of May at 26.9 ± 0.9°C and in the first week of June 25 ± 1°C. Humidity levels were 35–40% r.h. The barometric pressure was read every few hours on a mercury barometer and had typical values from 634 to 646 mm over a 4 week period.

The catholyte and anolyte temperatures were measured continuously using two thermistors (Thermometrics Inc., type SP60 BT 103 M1). They were enclosed in glass beads of diameter 0.14 mm and had a sensitivity of ±0.02°C. The glass bead

of the catholyte thermistor was cemented to the Pd cathode using thermally conductive epoxy (Thermalloy Inc., Thermalbond no. 4952). The anolyte thermistor was positioned close to the exterior of the Pt anode. The thermistors were calibrated in a water bath against a standard thermometer with a precision of ±0.02°C. The measured thermistor resistances were converted to temperature using an Omegabench™ software program from Omega Engineering Inc. in conjunction with a MacIntosh IIX computer.

Constant cell currents were applied with a precision constant current source (Keithley, model 228A). The potentials of the cell and cathode versus the reference electrode (where applicable) were read with multimeters (Keithley, model 179) and recorded on a hydrid recorder (Yokogawa, model HR 230). Temperatures and potentials were stored in the computer.

Experimental procedure

Before each experiment, the tritium contents of the electrolyte, pieces of Pt from the same wire spool from which electrodes were cut and the D_2 fill gas were determined. In addition, the D_2O in each new bottle for the preparation of 0.5 M D_2SO_4 and the deionized H_2O for the preparation of 0.5 M H_2SO_4 were analyzed for tritium. A Beckman LS 5000 TD liquid scintillation counter was employed for these analyses. For analysis of the liquids, 1 ml of liquid was added to 10 ml of scintillation cocktail (Beckman pseudocumene–xylene). For analysis of tritium in Pd, the Pd was acid digested and a distillation–gas recombination procedure in a closed system was used to capture all escaping tritium in liquid form [30]. Further details of the procedures have been published elsewhere [29,30].

Since an accurate value of the tritium contamination level was not supplied by the manufacturers, a tritium analysis procedure for D_2 gas was developed [34]. The recombination reaction of D_2 with O_2 gas on a Pt catalyst surface was used to obtain aliquots of heavy water for analysis. A gas-tight vessel was connected to a gas buret to measure the volume of D_2 gas recombined. An evacuated vessel containing a 12 cm^2 piece of catalyst was filled with D_2 gas. Oxygen was injected with a syringe through a septum and the D_2 displacement was measured. The recombined heavy water was rinsed out with distilled H_2O and analyzed for tritium.

No tritium analysis was performed on the fuel cell catalyst, epoxy and glassware. Any tritium contamination of these materials should show up to the same extent in the D_2O cells and the H_2O control cells and thus be recognized. No evidence for tritium contamination was found.

Pt leads of diameter 0.25 mm were spot-welded to Pd electrodes. The electrodes were rinsed in ethanol and deionized H_2O. The Pd wires were then palladized in $PdCl_2$ solutions in H_2O or D_2O using a cathodic current density of 15 mA cm^{-2} for 2 min. Finally, the electrodes were preloaded with H_2 gas or D_2 gas, employing a vacuum system described elsewhere [36]. The H/Pd or D/Pd loading ratio was determined by weighing before and after gas loading. Teflon tubing was slipped over the Pt leads and the electrodes were quickly introduced into the electrolytic cell. Gas preloading resulted in typical loading ratios of 0.45 to 0.75, and these values remained unchanged when exposure to laboratory air was limited to the manipulations mentioned above.

The electrolytic cells and manometer legs communicating with the cells were evacuated and then refilled with D_2 and H_2 gas at ambient pressure [33]. This assured proper and immediate functioning of the internal gas recombination catalyst by preventing the formation of oxygen chemisorption layers [37]. The vacuum was applied for 15–30 min and the pressure monitored with a mercury manometer to assure that the remaining pressure was due to water vapor (26.7 Torr at 27°C). The leak rate of air into the evacuated cell was established initially in one cell. Within 24 h, the mercury manometer reading remained stable when the ground glass joints were greased (Dow-Corning silicone high vacuum grease) and a vacuum rubber hose was used to connect the water manometer to the cell. During experiments, leak checks were performed periodically by pressurizing cells slightly. This was done by adjusting the position of the movable buret of the manometer and establishing that the level of the water column did not change with time, once an electrode was essentially fully loaded.

When starting the electrolysis, essentially no $D_2(H_2)$ gas was generated on the Pd. The O_2 gas generated on the Pt anode recombined with the prefilled D_2 (H_2) to form water. The amount of D_2 (H_2) consumed by reaction with the O_2 is precisely equivalent to the number of D (H) atoms absorbed by the Pd. Hence the decrease in the gas volume in the cell is a precise measure for the D/Pd (H/Pd) loading ratio. The gas volume stops changing when full loading is attained. Gas volume determinations were always performed with the manometer levels equalized so as to maintain ambient pressure in the cell [32,33]. The volume changes determined at a particular pressure and temperature were reduced to standard pressure and temperature, and the amount of D_2 absorbed by the Pd was determined from the universal gas equation. On the basis of the errors in measuring volume, pressure and temperature, we estimate that the overall error in the loading ratio determinations is ±5%.

After completing an experiment, which generally lasted for about a week, the electrolyte, Pd electrode and gas were analyzed for tritium and compared with the amounts of tritium present before the experiment. The Pd electrodes were cut into several pieces, of which four were analyzed individually.

RESULTS AND DISCUSSION

Pd and H / Pd loading ratio

To achieve D/Pd or H/Pd loading ratios approximately equal to unity reproducibly, it was found necessary to load and partially unload the Pd repeatedly with low current densities. The precise procedure and detailed loading results obtained

for a number of electrodes have been described elsewhere [38]. Typical results ... D and H loading measurements on Pd wires of diameter 2 mm and length ca. 3 ... (Hoover & Strong) are shown in Fig. 2. Both wires had been preloaded in D ... H_2 gas to loading ratios of 0.68 and 0.75 respectively. The cycling regime consis... of constant-current charging (loading) and discharging with currents between ... and 30 mA (current densities of ca. 5 to 15 mA cm^{-2}). The cell voltage (Pd vs. ... during discharge was not allowed to exceed +0.8 V to keep the formation of ... layers on the Pd to less than a monolayer [37] and to avoid O_2 evolution on the ... The pertinent currents for the seven charging and six discharging events are gi... in the figure caption.

In general, each additional cycle leads to higher loading but the increme... become smaller. The charging curve segments show a tendency to reach a limi... loading ratio if the charging period is long. After 250 h of cycling, of which 90 ... loading, the H/Pd loading ratio is 0.95. Similarly, after 280 h of cycling, the D ... ratio is 0.96.

The loading ratios of the eight 2 mm Pd wires, four cycled in 0.5 M D_2SO_4 ... four in 0.5 M H_2SO_4 are summarized in Table 1. Seven electrodes attained ... loading ratio of unity (within an error of ±0.05) and one electrode attained a v... of 1.07.

Loading ratios of unity and above have been attained by other groups, emplo... ing one of four methods: (1) low temperature electrolysis in electrolytes w... organic solvents [39–41], (2) long-term electrolysis at ambient temperatu... [13,33,42], (3) loading in the gas phase at pressures of several 10000 atm [43,44] ... (4) hydrogen ion bombardment of thin Pd films, followed by sample quench... from 300°C in liquid N_2 [45].

Neutron diffraction and scattering studies show that D and H occupy ... octahedral sites in the f.c.c. structure of Pd [46–48] corresponding to a load... ratio of unity. However some evidence has been presented that H and D ... occupy the tetragonal sites, particularly at very low temperatures (< 5... [45,49,50], resulting in loading ratios of 1.33 [45].

While it cannot be excluded that tetragonal sites in the Pd are occupied by D ... H in the present study, it is regarded as more likely that some D or H is contain... in internal voids or microcracks, or that D or H clustering has occurred ... dislocations. Excess volume (beyond that due to lattice expansion) up to 32% ... recently been found in Pd that had been exposed to repeated loading–unload... cycles [28].

In another study [51], employing 2 mm diameter Pd wires from the s... supplier (Hoover & Strong) but conducted in a cell of very different design, ... have not been able to attain D/Pd ratios exceeding 0.84. This could be due to ... fact that the Pd electrodes were only 1.8 cm long and that the Pt anode was v... close to the Pd cathode. This could have encouraged the loss of D from the ends ... the Pd electrode owing to lower current densities and hence smaller overvolta... at the ends.

...BLE 1

...um analysis of electrolyte, Pd and gas

...riment	1		2		3		4	
...at D/Pd > 0.8/h	163.8		169.7		144.4		483.5	
...olyte	D_2SO_4 + Li_2SO_4	H_2SO_4 + Li_2SO_4	D_2SO_4	H_2SO_4	D_2SO_4	H_2SO_4	D_2SO_4	H_2SO_4
...ing ratio								
... Pd, H/Pd	0.99	1.03	0.96	0.95	1.02	1.07	0.98	1.01
...lectrolyte/10^{10} atoms								
...fore	0.38	ND	0.29	ND	10 *	ND	0.24	ND
...ter	19	ND	8.0	ND	14	ND	10	ND
... Pd/10^{10} atoms								
...fore	ND	ND	ND	ND	ND	ND	ND	ND
...ter	1.7	ND	16	ND	21	ND	4.7	ND
...as/10^8 atoms								
...fore	1.8	NM	1.8	NM	1.8	NM	1.8	NM
...ter	1.8	NM	8.3	NM	62	NM	NM	NM
...d/10^{10} atoms								
...fore	0.4	ND	0.31	ND	10	ND	0.26	ND
...ter	21	ND	9.7	ND	17	ND	15	ND
...erated/10^{10} atoms								
...cement factor	52.5	ND	31.2	ND	1.7	ND	57.7	ND
...ic T yield/ ... atoms cm^{-2}	11	ND	4.5	ND	4.3	ND	8.8	ND
...ge rate of T gener- ... 10^{-1} atoms cm^{-2} s^{-1}	20	ND	7.4	ND	8.3	ND	5.1	ND

...ch of D_2O with high T content.
...not detected
...not measured

...um yield

...total of eight experiments were carried out, involving 16 cells on which tritium ...alyses were performed. In every experiment, one Pd cathode (of identical origi... ...s employed in each of a heavy water cell and a light water control operated in ...trical series. Three different types of Pd electrodes were used: (a) 1 mm ...meter Pd wires from Johnson Matthey (three experiments), (b) 2 mm × 0.5 mm ... 5% Li alloy ribbons (one experiment) and (c) 2 mm diameter Pd wires from ...over & Strong (four experiments). No tritium generation was observed on the 1 ...m Pd wires and the Pd + Li alloy, despite the attainment of loading ratios of ...ity in all cases but one (where the cycling time was insufficiently long). In ...ntrast, all Hoover & Strong 2 mm Pd wires in D_2SO_4 showed tritium generation ...ll above background, whereas none of the four identical Pd control electrodes in ... SO_4 showed any detectable tritium.

Table 1 summarizes the results of all four experiments conducted with 2 mm ...meter Pd wires from Hoover & Strong. Deuterium loading or charging always ...ceded tritium analysis. In the second line of the table, the times are given for

which the cells were operated at an average D/Pd ratio greater than 0.8. For th low current densities (5–15 mA cm^{-2}) and long charging times generally employe in this study, the D loading is expected to be rather uniform throughout the Pd that the average D/Pd ratio will be fairly representative of the entire Pd. Fro further results, to be published elsewhere, it appears that tritium is predominant generated when the average loading ratio exceeds 0.8. The total times at D/Pd 0.8 were used to calculate average tritium generation rates, given at the bottom the table. The total amounts of tritium generated in the four cells are surprisingl uniform, ranging from a low value of 7×10^{10} T atoms cm^{-2} to a high value 2.1×10^{11} T atoms cm^{-2} of Pd surface. Alternatively, when referred to u weight, the values range from 8.4×10^{10} to 2.1×10^{11} T atoms g $Pd)^{-1}$. Althou the results of this study (see below) in conjunction with those of others [12,14,28,4 favor the generation of tritium in the Pd interior rather than at its surface, th yield in this study is referred to unit area to allow ready comparison with th results of other authors who usually mention an electrode area but no electro weight.

Below the tritium yields in Table 1 are given tritium enhancement factors wh express the ratio of the total tritium present in the cell after the experiment to th total tritium present before the experiment. Three of the four cells show enhan ment factors ranging from 31 to 58. The fourth cell has an enhancement facto only 1.7, owing to the fact that in this cell a new batch of heavy water with tritium level 30 times larger than the tritium content of the heavy water in th other experiments was inadvertently used. It is interesting to note that, indepe dent of the 30 times higher initial tritium content of the electrolyte, the amount tritium generated per unit area and time is not much different from the oth electrodes. This result is not surprising if the tritium is generated inside the Pd a if the T/D ratio is significantly larger in the Pd than in the D_2SO_4, as will b shown below.

Table 1 also summarizes average tritium generation rates, averaged over th time at which the electrode had a loading ratio exceeding 0.8 ± 0.05 and related unit area. The values run from 5.1×10^4 to 2×10^5 T atoms cm^{-2} s^{-1}, equivale to values from 0.9×10^5 to 3.7×10^5 T atoms g^{-1} s^{-1}.

Among the groups that have found tritium in heavy water electrolysis on Pd (in LiOD solutions), the results are highly variable among different groups and ev within the same group. Fleischmann et al. [1] reported relatively low tritiu accumulations of 50–100 dpm ml^{-1}, corresponding to 3×10^9 to 6×10^9 T atom cm^{-2}. Packham et al. [11] found values from 5.1×10^{11} to 1.8×10^{14} T atoms cm in the electrolyte of nine cells and no tritium in 12 other cells. The highest valu 1×10^{15} T cm^{-2}, reported by Bockris et al. [18]. The values found by vario groups at BARC [12] in 21 cells ranged from 4×10^9 to 1.7×10^{14} T cm^{-2}. In nin of these cells, the values ranged from 8×10^{10} to 6×10^{12} T cm^{-2}. Adzic et al. [1 found tritium generation in six out of nine cells with yields ranging from 3.1×10 to 3.1×10^{11} T cm^{-2}, equivalent to enhancement factors ranging from 6.2 to 5 Storms and Talcott [14] performed experiments on a large number of cells an

nerated tritium in 11 out of approximately 100 cells. The tritium yield ranged om about 5×10^{10} to 3×10^{11} T cm^{-2}. Values of 1.2×10^{11}–1.9×10^{11} [6], $\cdot 10^{10}$ [20] and 2.5×10^{10}–3×10^{10} T/cm^2 [24] were reported by three other roups.

Thus the results from 10 groups vary from 3×10^9 to 1×10^{15} T atoms cm^{-2}, ith seven of these reporting values from 2.5×10^{10} to 6×10^{12} T atoms cm^{-2}.

itium distribution between the three phases

According to Table 1, the largest amount of tritium accumulates in the liquid hase and by far the smallest amount in the gas phase. However, the distribution tritium in the three phases is usually compared on the basis of the T/D atomic tios. This has been done in Table 2. Also given in Table 2 are the ratios of the D values in metal/liquid etc. To distinguish these ratios from equilib h separation factors, they have been designated as "non-equilibrium distribution actors." The T/D distribution factors Pd/gas and Pd/liquid have very large lues, ranging from 37 to 233. In contrast, typical equilibrium isotopic separation actors D/H and T/H between Pd and gas are 0.42 and 0.37 respectively (at 25°C 2]. Values between 0.2 and 0.3 have been determined for the separation factor H (metal/solution) at 25°C [53]. The large values of the distribution factors und in the present study indicate that tritium has been generated in the Pd and at there has been insufficient time for it to diffuse out. Therefore the distribu- n over the three phases is far removed from equilibrium conditions, as described the equilibrium separation factors.

Results obtained by Storms and Talcott-Storms [28] on deliberately tritium- ed Pd cathodes tend to confirm this interpretation. A Pd button had a T/D tio of 1.22×10^{-8} prior to use as a cathode in 0.1 M LiOD, i.e. about 10^4 times ger than the values in this study. After 120 h of cathodic polarization at 35 mA $^{-2}$, the T/D ratio in the solution was 1.8×10^{-13}, in the D_2 gas it was 2×10^{-12} d in the Pd it was almost unchanged at 1.21×10^{-8}. Thus the non-equilibrium tribution factors were T/D (metal/liquid) = 6.7×10^4 and T/D (metal/ga 10^3, even larger than in the present study. Clearly, most of the tritium in the

BLE 2

D ratios and non-equilibrium distribution factors

periment	1	2	3	4
(T/D) liquid	7.6	3.2	5.6	3.5
(T/D) metal	2.8	2.6	3.5	7.8
(T/D) gas	1.2	5.5	41	NM
D (metal/liquid)	37	81	63	223
D (metal/gas)	233	47	85	NM
D (liquid/gas)	6.3	0.6	0.14	NM

M, not measured.

Pd had not diffused out during 120 h, thus maintaining a highly non-equilibri- distribution over the three phases.

At least two groups [12,42] have shown that tritium continues to be released i many days into the electrolyte or into fresh D_2O from D-loaded Pd after long-ter- cathodic polarization in LiOD solutions. This behavior corresponds to slow dif- sion of tritium from the interior of the Pd into the liquid phase with a diffusi- coefficient of the order of 10^{-8} cm^2 s^{-1}, a value well within the range of know diffusion coefficients [54], particularly for highly loaded Pd [55].

Local tritium distribution in Pd wire cathodes

A closed-system acid digestion method described elsewhere [30] was used determine the tritium in the Pd quantitatively. Figures 3(a) and 3(b) show t tritium spectra of a tritium standard (1000 dpm ml^{-1} of tritium in H_2O) and o solution containing the distillate and recombinate from a piece of the Pd cath used in experiment 3 of Table 1. The spectrum of the distillate has its maximum the same channel 225 as the standard, identifying the species extracted from Pd as tritium.

The tritium distributions in the four Pd cathodes are shown in Fig. 4. In t three experiments where the ends of the palladium wires were analyzed separat from the center sections, comparatively much less tritium is found at the ends the wires compared with the center. The eight pieces near the centers of the fo electrodes show a surprisingly narrow band of values namely, from 1.2×10^{1} 8.9×10^{10} T atoms (gPd)$^{-1}$. It appears that the ends of the Pd wires either did n charge as efficiently as the center regions or that tritium escaped from the ends more readily.

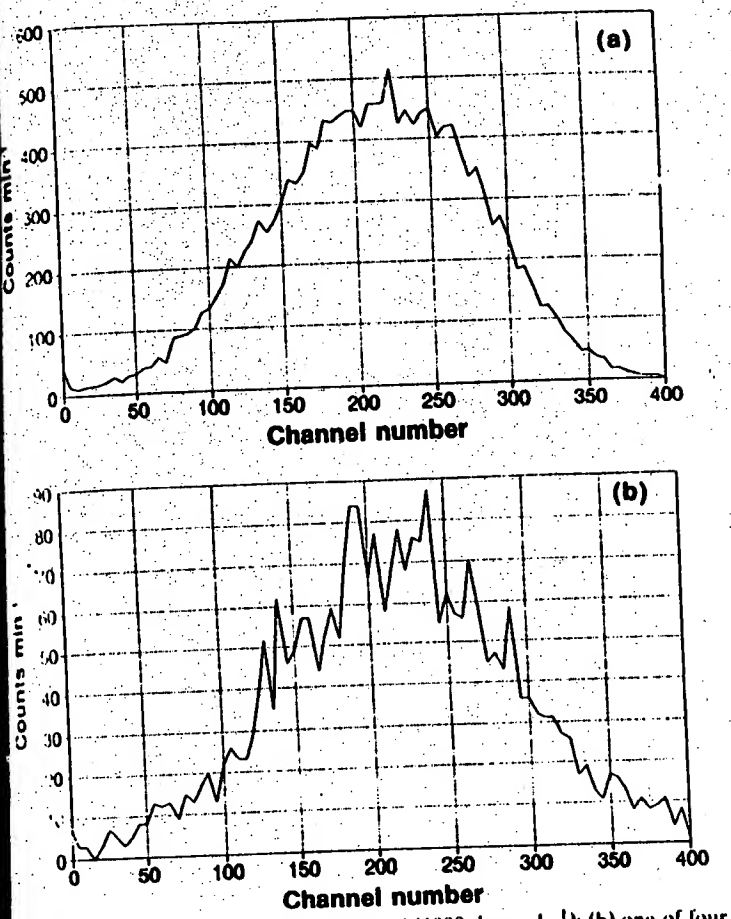
Significantly, the four Pd cathodes cut from the same Pd wire and employed H_2SO_4 under the same conditions and at the same time as the four Pd electrod in D_2SO_4 did not show any tritium within the detection limit of the analysis. 5×10^8 T atoms (g Pd)$^{-1}$.

In addition, 54 as-manufactured pieces of 2 mm Pd wire from the same suppl (Hoover & Strong) were analyzed for tritium and did not contain any triti within the detection limit. Thus it appears that the tritium found in all four 2 m Pd cathodes loaded in D_2SO_4 is due to accidental tritium contamination of as-received material or to handling thereafter.

Lastly, the recombination catalyst has to be ruled out as a source of triti since no tritium was found either in the four H_2SO_4-filled cells or in the as-received Pd samples employing the same type of catalyst in the analyt procedure as in the electrolyte cells.

Since (1) all four D_2SO_4 cells with 2 mm Pd electrodes showed considera more tritium after than before the electrolysis and nothing was added to the tigh closed cells during the experiments, * and (2) the four Pd electrodes have m

* With the exception of cell 4 where electrolyte samples were removed and fresh D_2O was added.



Tritium spectra: (a) tritium standard (1000 dpm ml^{-1}); (b) one of four Pd electrode pieces after iment 3 of Table 1 applying a closed-system analytical procedure described elsewhere [29].

gher T/D atomic ratios than the liquid or gas phase, the tritium was apparently nerated in the highly D-loaded Pd. Only nuclear reactions occurring in the D-loaded Pd could have led to the observed tritium. While the nature of these nuclear reactions remains to be established, it is clear that deuterium and tritium are intimately involved in them.

CONCLUSIONS

A cyclic charge–discharge regime of Pd in aqueous sulfuric acid solutions, employing low current densities of typically only 5–15 mA cm^{-2}, leads to the reproducible attainment of H/Pd and D/Pd loading ratios of 1 ± 0.05 as observed for 16 out of 16 Pd electrodes. Tritium accumulations up to 57 times background

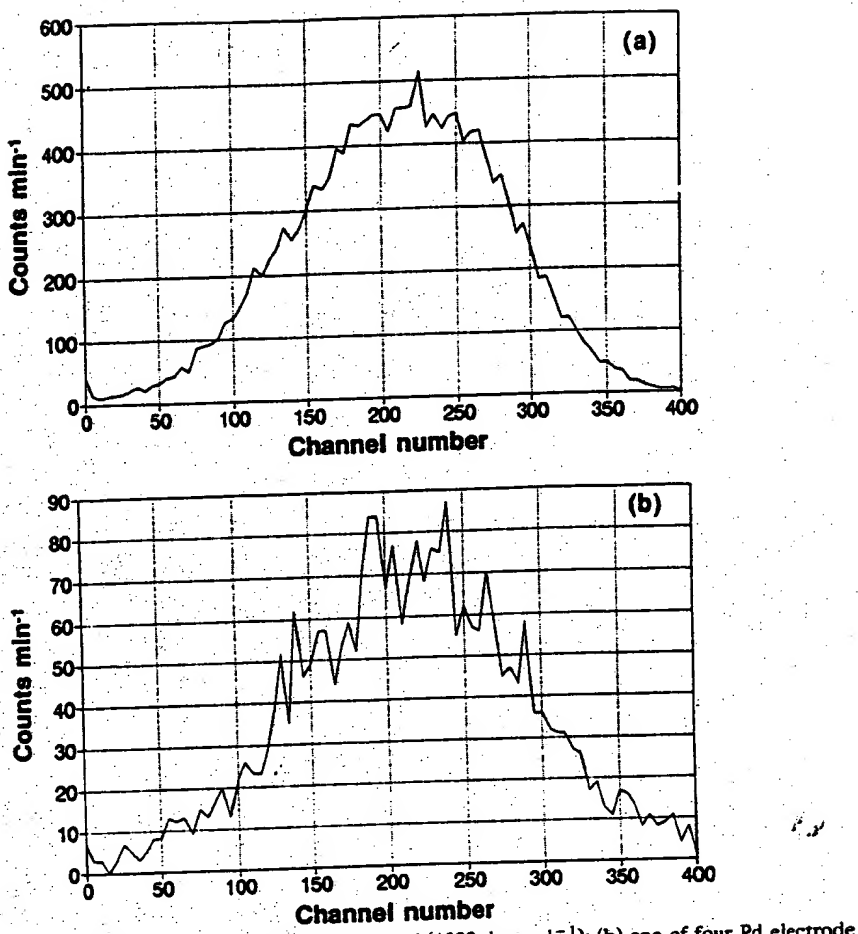


Fig. 3. Tritium spectra: (a) tritium standard (1000 dpm ml^{-1}); (b) one of four Pd electrode pieces after experiment 3 of Table 1 applying a closed-system analytical procedure described elsewhere [29].

higher T/D atomic ratios than the liquid or gas phase, the tritium was apparently generated in the highly D-loaded Pd. Only nuclear reactions occurring in the D-loaded Pd could have led to the observed tritium. While the nature of these nuclear reactions remains to be established, it is clear that deuterium and tritium are intimately involved in them.

CONCLUSIONS

A cyclic charge–discharge regime of Pd in aqueous sulfuric acid solutions, employing low current densities of typically only 5–15 mA cm^{-2}, leads to the reproducible attainment of H/Pd and D/Pd loading ratios of 1 ± 0.05 as observed for 16 out of 16 Pd electrodes. Tritium accumulations up to 57 times background

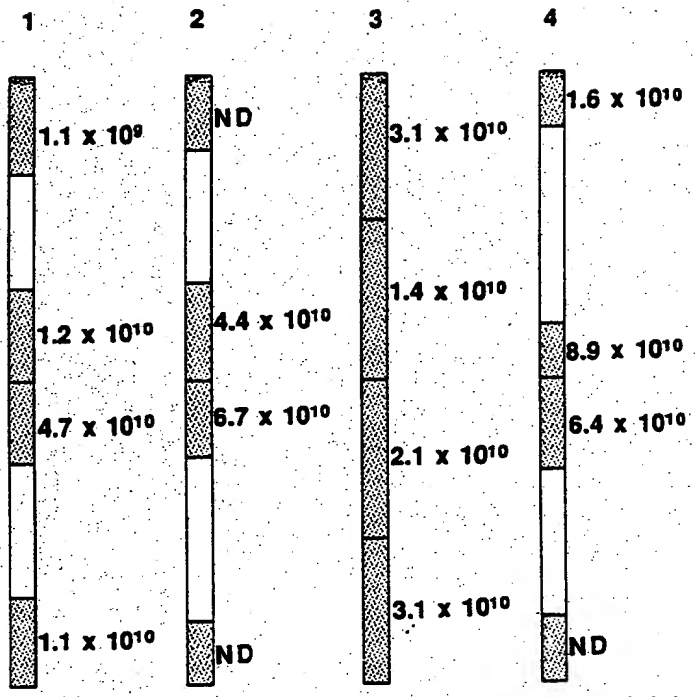


Fig. 4. Axial tritium distribution in Pd cathodes after D_2O electrolysis in experiments 1–4 of Table 1 using analytical procedure described elsewhere [29]. ND, not detected (the detection limit is 5×10^8 atoms) $(gPd)^{-1}$. The numbers give the numbers of atoms per gram Pd.

were found in four out of four tightly closed heavy water cells, employing Pd electrodes of a certain type, whereas no tritium above background was found in four light water control cells run with Pd electrodes from the same wire under the same conditions and at the same time. No tritium was found in four heavy water cells employing Pd electrodes of another type or a Pd + Li alloy electrode, despite having attained D/Pd ratios of 1 ± 0.05. D/Pd loadings exceeding 0.8 ± 0.05 appear to be a necessary but not sufficient condition for tritium generation. Metallurgical factors also appear to be significant. The difficulty in attaining D/Pd loadings exceeding 0.7 with continuous rather than cycling loading methods, coupled with the as yet unknown effects of the Pd metallurgy, probably account for the failure of many groups to observe measurable tritium generation. Specific tritium yields were between 4.3×10^{10} and 1.1×10^{11} atoms cm^{-2} compared with a range of values from 2.5×10^{10} to 6×10^{12} atoms cm^{-2} as determined by seven of ten other groups reporting tritium. Average tritium generation rates in the four heavy water cells ranged from 5×10^4 to 2×10^5 atoms s^{-1} cm^{-2}. This is equivalent to an average power level of the order of 10^{-7} W, which is too small to be detected. The T/D distribution over the three phases—Pd, electrolyte and gas —is highly non-equilibrium, with the T/D ratio approximately 100 times larger in

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the Pd than in electrolyte or gas. This indicates that the tritium is generated inside the Pd, where it is found at levels of up to 9×10^{10} atoms $(g\ Pd)^{-1}$. Based on previous analyses of 54 as-manufactured Pd samples of the same type of 2 mm wire from the same supplier, which had resulted in no measurable tritium within a detection limit of 5×10^{8} atoms $(g\ Pd)^{-1}$, it appears that the tritium in the four Pd electrodes was not caused by accidental contamination of the Pd. Since up to 57 times more tritium was found in the tightly closed cells after heavy water electrolysis compared with that present before, the tritium must have been generated in the cells. Based on the large T/D ratios in the Pd electrodes, it is concluded that the tritium was generated inside the Pd; only nuclear reactions, whose nature is as yet unknown, could have produced the observed tritium.

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Abstract

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INTRODUCTION

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